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THESIS

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AN EQUIVALENT RECTANGULAR WAVEGUIDE MODEL FOR FINLINE

by

Thomas A. Bush

December 1989

Thesis Advisor Jeffrey B. Knorr

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An Equivalent Rectangular Waveguide Model for Finline

by

Thomas A. Bush
Captain, United States Army
B.S., United States Military Academy, 1978

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

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December 1989

ABSTRACT

This thesis describes an equivalent rectangular waveguide model for finline. The model is used to predict the wavelength and characteristic impedance of finline based on numerical data generated by the spectral domain analysis technique. A comparison of the voltage-power and voltage-current definitions of characteristic impedance is provided as justification for using this approach. The model is applicable to all finlines with centrally positioned fins, aspect ratio of 2, and dielectric constant of 2.22. Results are provided for $\frac{w}{b} = \{0.01, 0.02, 0.05, 0.10, 0.20, 0.50, 1.00\}$ and dielectric substrate thicknesses of 0 to 30 mils in 5 mil increments. The model is designed so that it can be easily implemented in most of the commercially available microwave CAD software packages.

c. 1

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I. INTRODUCTION

A. BACKGROUND

Finline was first proposed as a transmission structure by P.J. Meier in 1974 [Ref.1]. Since its inception, finline has gained in importance as a transmission medium in millimeter wave engineering applications. Finline has virtually replaced microstrip as the medium for constructing millimeter wave circuits due to the former's eased production tolerances, higher mode suppression, broad single-mode bandwidth, and compatibility with solid-state chip devices.

A 3-dimensional view of unilateral finline is shown in Figure 1 on page 2. In its most general form, it consists of metal fins printed on a dielectric substrate which is mounted in the E-plane of a rectangular waveguide. The substrate is normally thin and has a low dielectric constant. Both the fin gap width, w, and the dielectric substrate thickness, D, are variable parameters for purposes of this thesis. Also, the dielectric constant, ε_r, of region 2 is fixed at 2.22, the fins are centrally located within the waveguide, and the aspect ratio, $\frac{a}{b}$, equals 2.

B. RELATED WORK

Finline has been studied extensively during the past 15 years, with over 350 articles published on the subject. One of the first papers concerned with the modeling of finline was published by Saad and Schunemann in 1981[Ref.2]. This paper modeled both unilateral and bilateral finlines by an infinite set of rectangular waveguide modes. A subsequent work by Pramanick and Bhartia provided a model for the apparent characteristic impedance of finline presented in terms of per-unit-length capacitance of the fins.

A particularly relevant work concerning the spectral domain analysis of finline was published by Knorr and Shayda in 1980[Ref.3]. A Master's thesis by Kim updated this work by reformulating the characteristic impedance equations of the program [Ref.4]. The spectral domain analysis program developed in these two works is used to generate the numerical data upon which this thesis is based. The rationale for using this approach is presented in a later section.

C. PURPOSE

The use of Computer-Aided Design (CAD) in microwave engineering has grown in significance during the past decade. It provides a means of analyzing and designing a

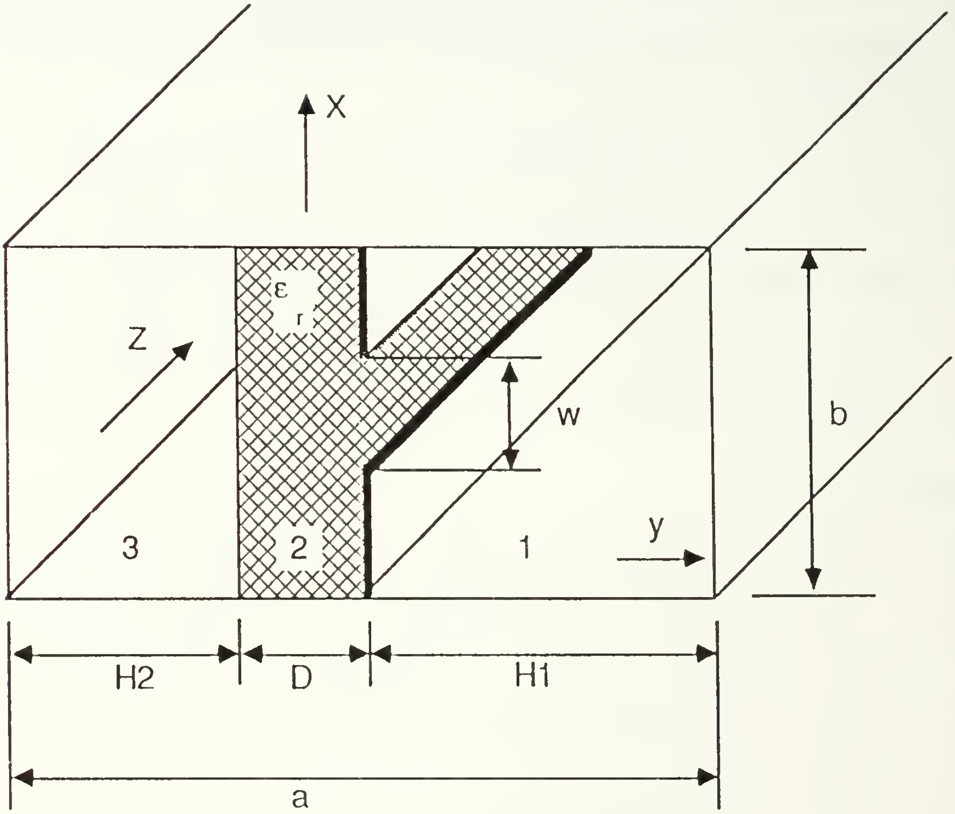

Figure 1. 3-Dimensional view of unilateral finline.

device without the costly process of prototype constuction. The utilization of any device in CAD is based upon an element library. The development of a element model and associated software for that library can also be a costly and tedious process.

The purpose of this thesis is to develop a model for finline which can accurately predict the characteristic impedance and wavelength for varying frequency, substrate thickness, and fin gap width. The model is to utilize an existing element library of a CAD microwave circuit simulator.

Chapter II of this thesis discusses the different definitions of characteristic impedance and provides a graphical comparison of the results. Chapter III describes the underlying concepts associated with the model. Model development and applicable results are presented in Chapter IV. Chapter V presents some conclusions and ideas for future pursuit.

II. DEFINING CHARACTERISTIC IMPEDANCE

A. BASIC DEFINITIONS

The concept of characteristic impedance is invaluable in microwave circuit design since the distribution of microwave energy among the elements, through the interconnections, is decided by the impedance [Ref.5]. There are three basic definitions of characteristic impedance applicable to the study of finline. These definitions are:

$$Z_{0V} = \frac{(V_0)^2}{2P_{avg}} \tag{1}$$

$$Z_{0I} = \frac{2P_{avg}}{(I_0)^2} \tag{2}$$

$$Z_0 = \frac{V_0}{I_0} \tag{3}$$

where voltage is defined as the line integral of the electric field over the shortest path between the fins and the current is the total longitudinal current flowing in the structure.

Equations 1 and 2 are referred to as the voltage-power and current-power definitions, respectively. These two equations are based upon the usual definitions of power dissipation in a resistor. Equation 3 is referred to as the voltage-current definition and was first proposed by Hofmann in 1977 [Ref.6].

The two most commonly used definitions are the voltage-power and voltage-current definitions. The voltage-power definition is commonly used in the design of finline filters and tapers, while the voltage-current definition is appropriate in the design of finline switches. The remainder of this chapter is devoted to comparing these two definitions in order to determine which one is more applicable to the development of the finline model.

B. COMPARISON OF IMPEDANCE DEFINITIONS

1. Voltage-Power Definition

The voltage-power impedance is computed using the spectral domain analysis program. A thorough analytical derivation is presented in [Ref.4: pp. 25-26] and is not duplicated here. Numerical data on characteristic impedance and wavelength were generated from the spectral domain analysis program as a part of this thesis. These results are contained in the Appendices.

2. Voltage-Current Definition

In addition to the definition described in Equation 3 above, characteristic impedance relative to voltage-current can also be expressed as:

$$Z_0 = Z_{0\infty}[1 - (\frac{\lambda_0}{\lambda_{cr}})^2]^{-\frac{1}{2}} \tag{4}$$

where λ_{cr} and $Z_{0\infty}$ are the cutoff wavelength and the characteristic impedance at infinite frequency, respectively, of a ridged waveguide of identical dimensions. The characteristic impedance at infinite frequency was developed by Sharma and Hoefer [Ref.7], and is defined as:

$$Z_{0\infty} = \frac{120\pi^2(\frac{b}{\lambda_{cr}})}{(\frac{b}{w})\sin(\frac{\pi D}{\lambda_{cr}}) + [\frac{B_0}{Y_0} + \tan(\frac{\pi(a-D)}{2\lambda_{cr}})]\cos(\frac{\pi D}{\lambda_{cr}})} . \tag{5}$$

The normalized susceptance, $\frac{B_0}{Y_0}$, is approximated by:

$$\frac{B_0}{Y_0} \simeq (\frac{2b}{\lambda_{cr}}) \ln \csc(\frac{\pi w}{2b}). \tag{6}$$

This approximation is valid for thin substrate thicknesses and low dielectric constants, $\varepsilon_r \leq 2.5$. The cutoff wavelength in Equations 5 and 6 is defined as:

$$\lambda_{cr} = \frac{b}{(\frac{b}{2a})[1 + (\frac{4}{\pi})(1 + 0.2\sqrt{\frac{b}{a}})(\frac{b}{a}) \ln \csc(\frac{\pi w}{2b})]^{-\frac{1}{2}}} . \tag{7}$$

C. COMPARISON OF DEFINITONS

Comparisons of the voltage-power and voltage-current definitions for various fin-gap-to-height ratios are shown in Figures 2 through 6. Characteristic impedance, in ohms, is plotted relative to frequency for a WR (28) finline across the Ka-band, 26-40 GHz, in steps of 2 GHz. The voltage-power definition is depicted as a dotted line and the voltage-current as a solid line in each figure. Graphs were constucted by plotting data points, marked as circles or squares, and then connecting the points with a best fit curve.

An analysis of each set of curves reveals that the two definitions differ by a constant value for each value of $\frac{w}{b}$. This direct relationship allows the freedom of selecting either definition for purposes of model development. The model prediction of characteristic impedance could then be scaled appropriately to change to a different impedance definition.

The voltage-power definition of characteristic impedance was selected for purposes of this thesis. This choice permits the use of the spectral domain analysis program to generate numerical data required for model development. The spectral domain analysis technique has demonstrated a high degree of accuracy in predicting both finline wavelength and characteristic impedance.

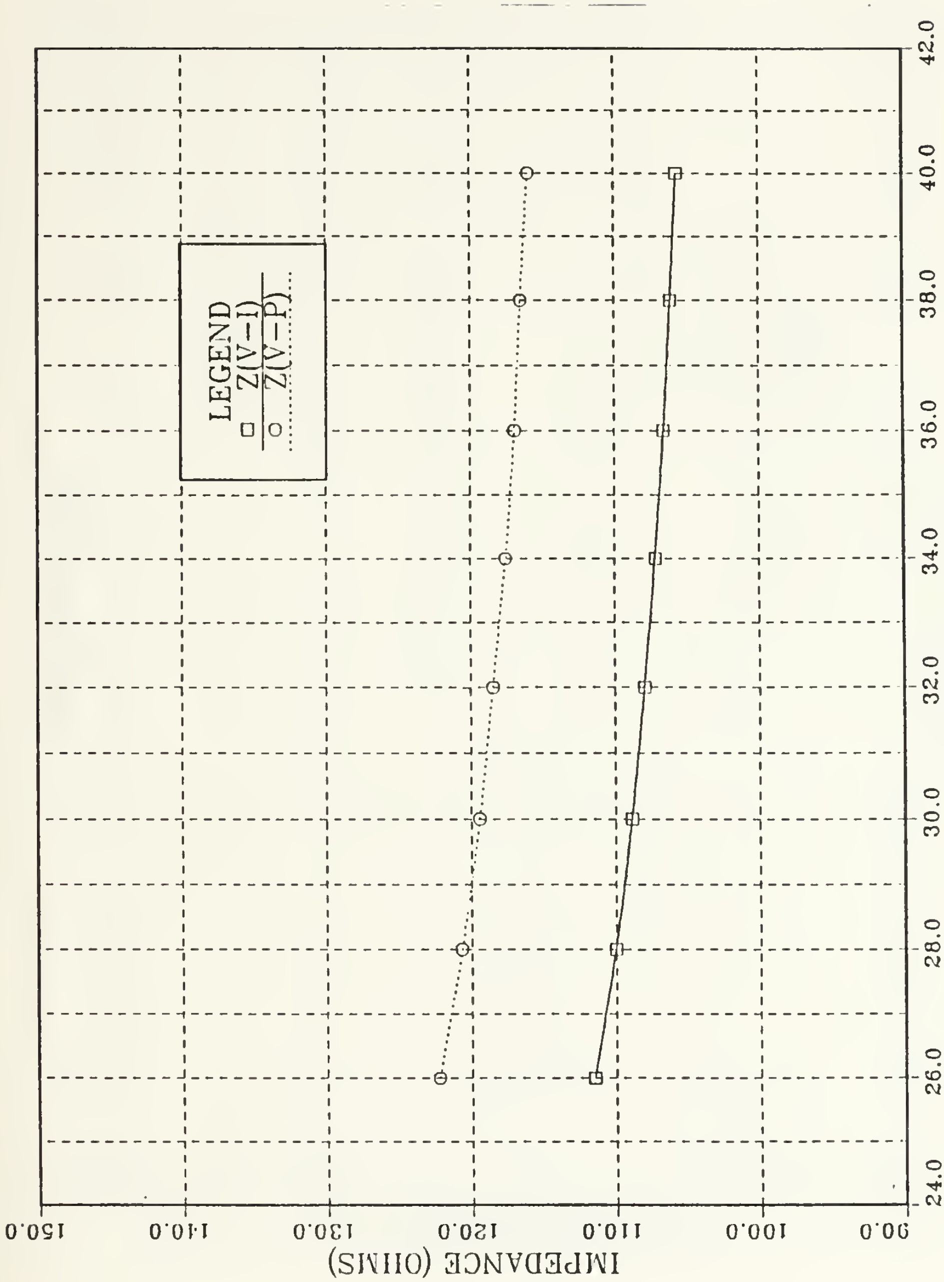

Figure 2. Comparison of impedance definitions, $\frac{w}{b}$ =0.01

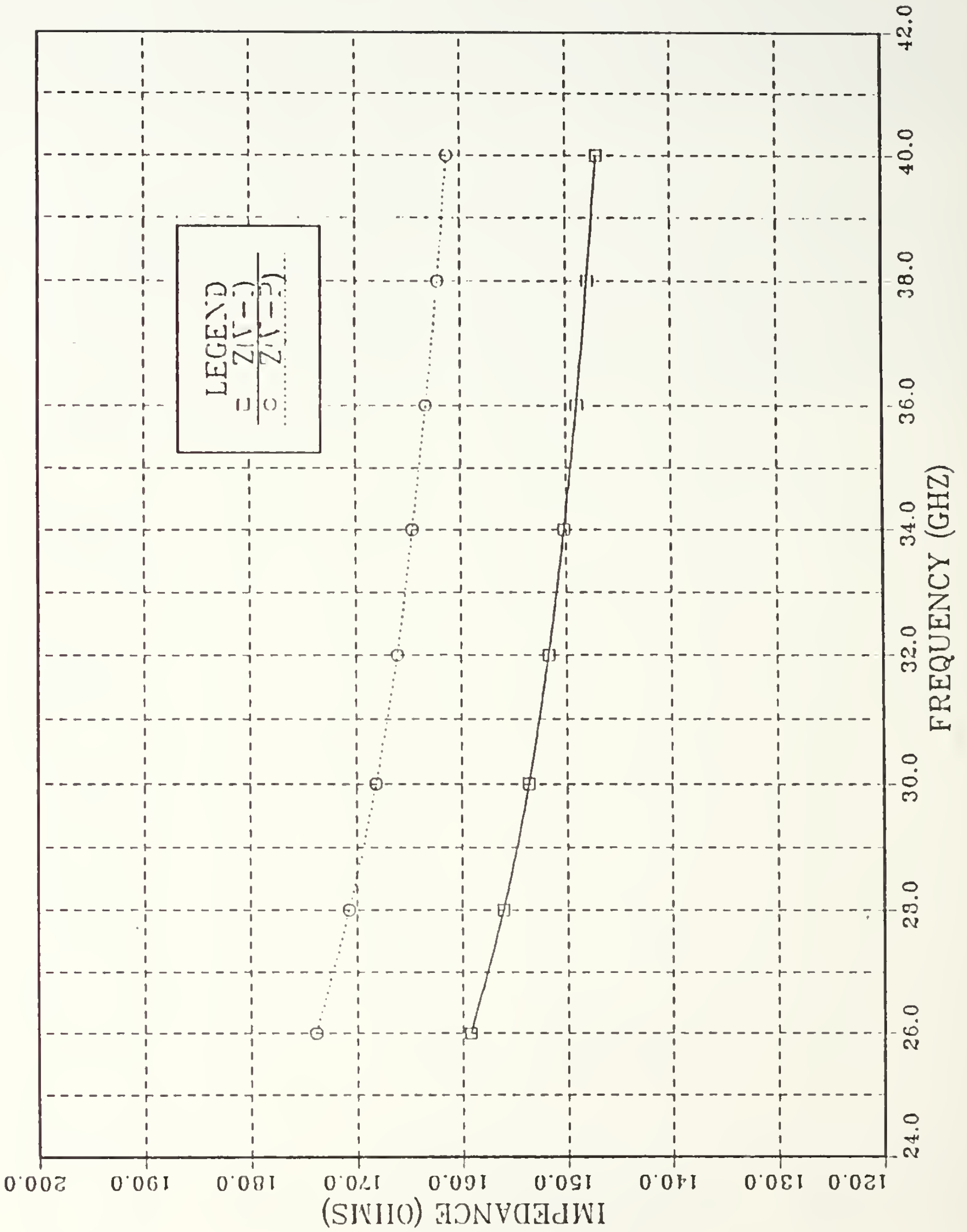

Figure 3. Comparison of impedance definitions, $\frac{w}{b}$ =0.05

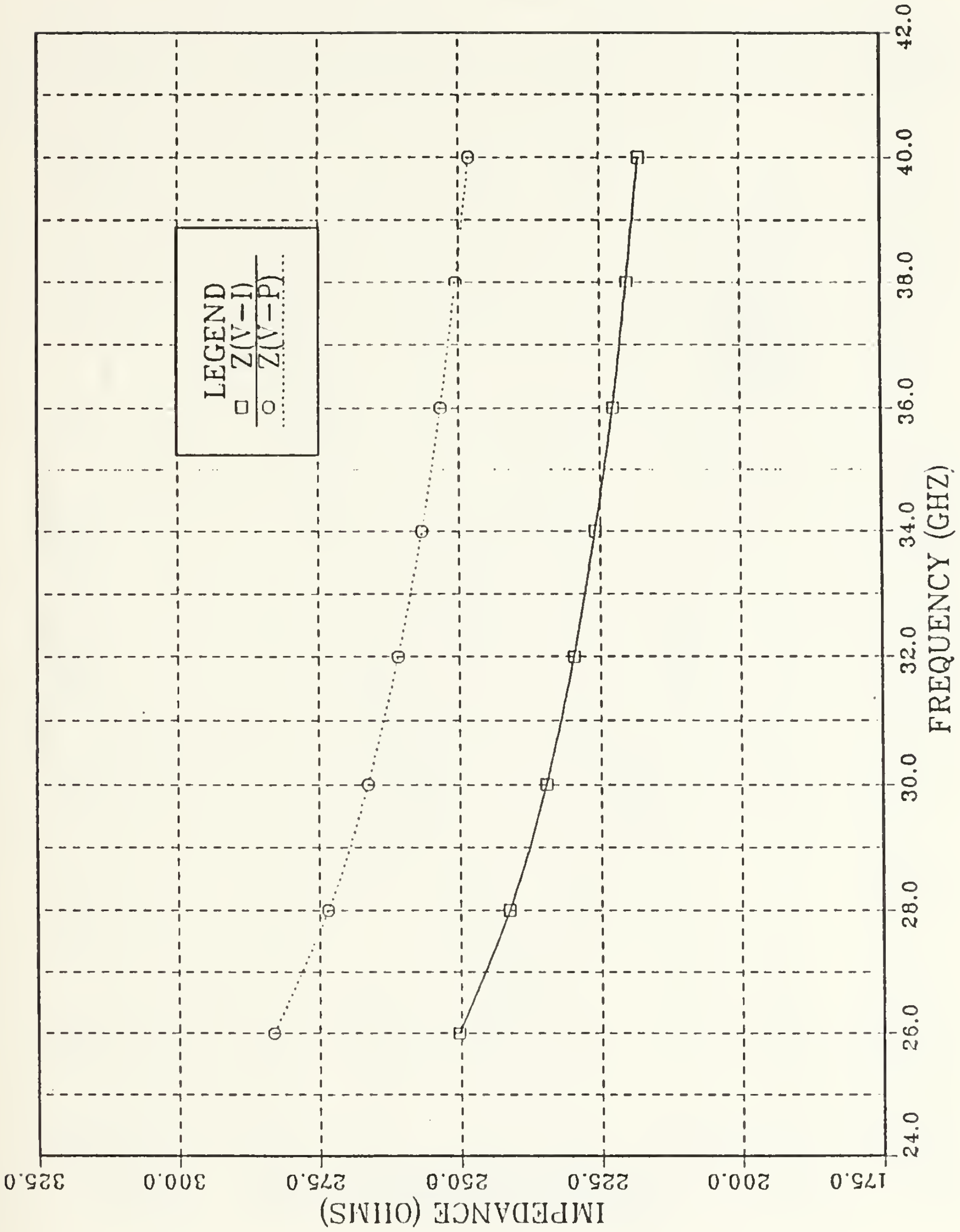

Figure 4. Comparison of impedance definitions, $\frac{w}{b}=0.20$

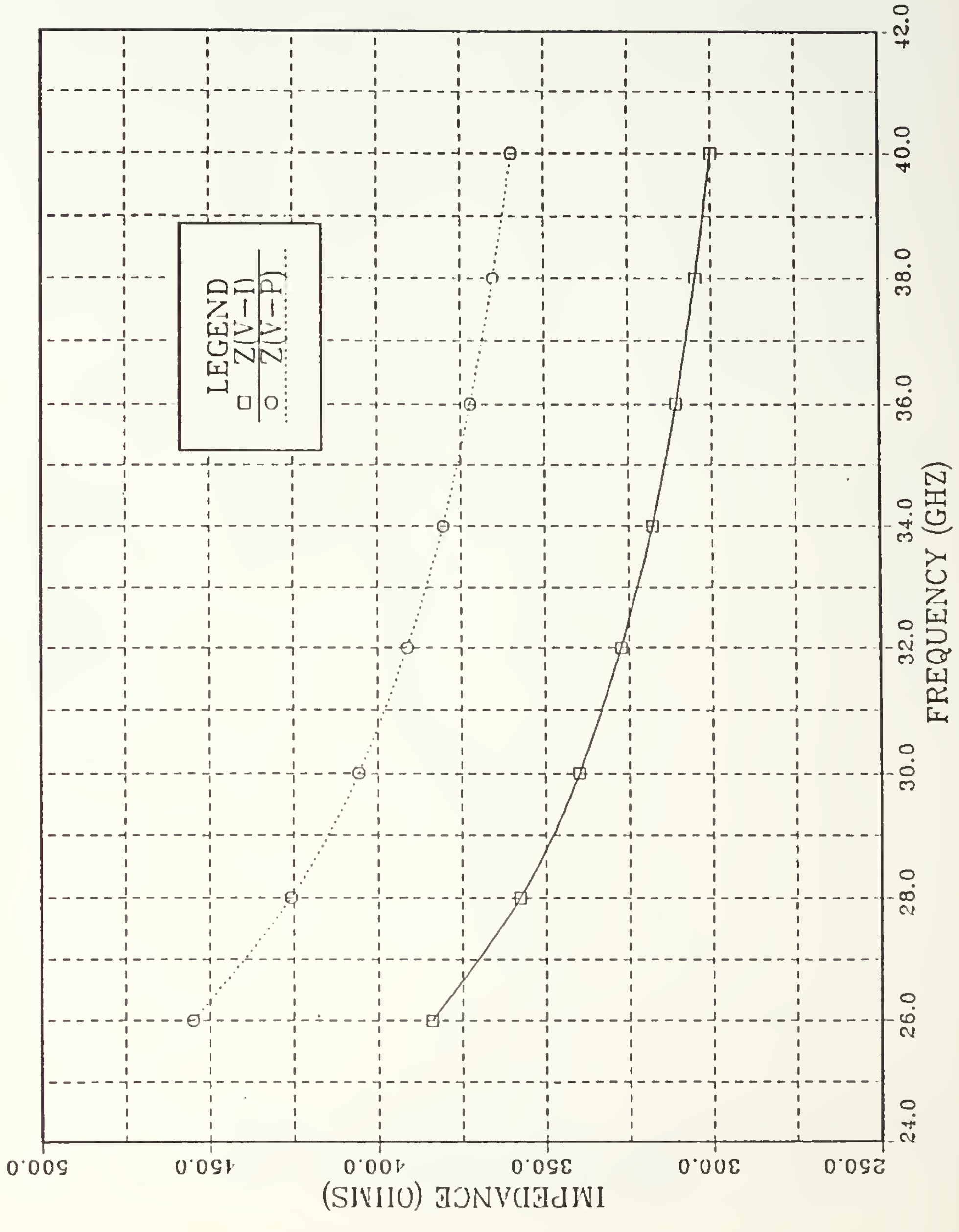

Figure 5. Comparison of impedance definitions, $\frac{w}{b}$ =0.50

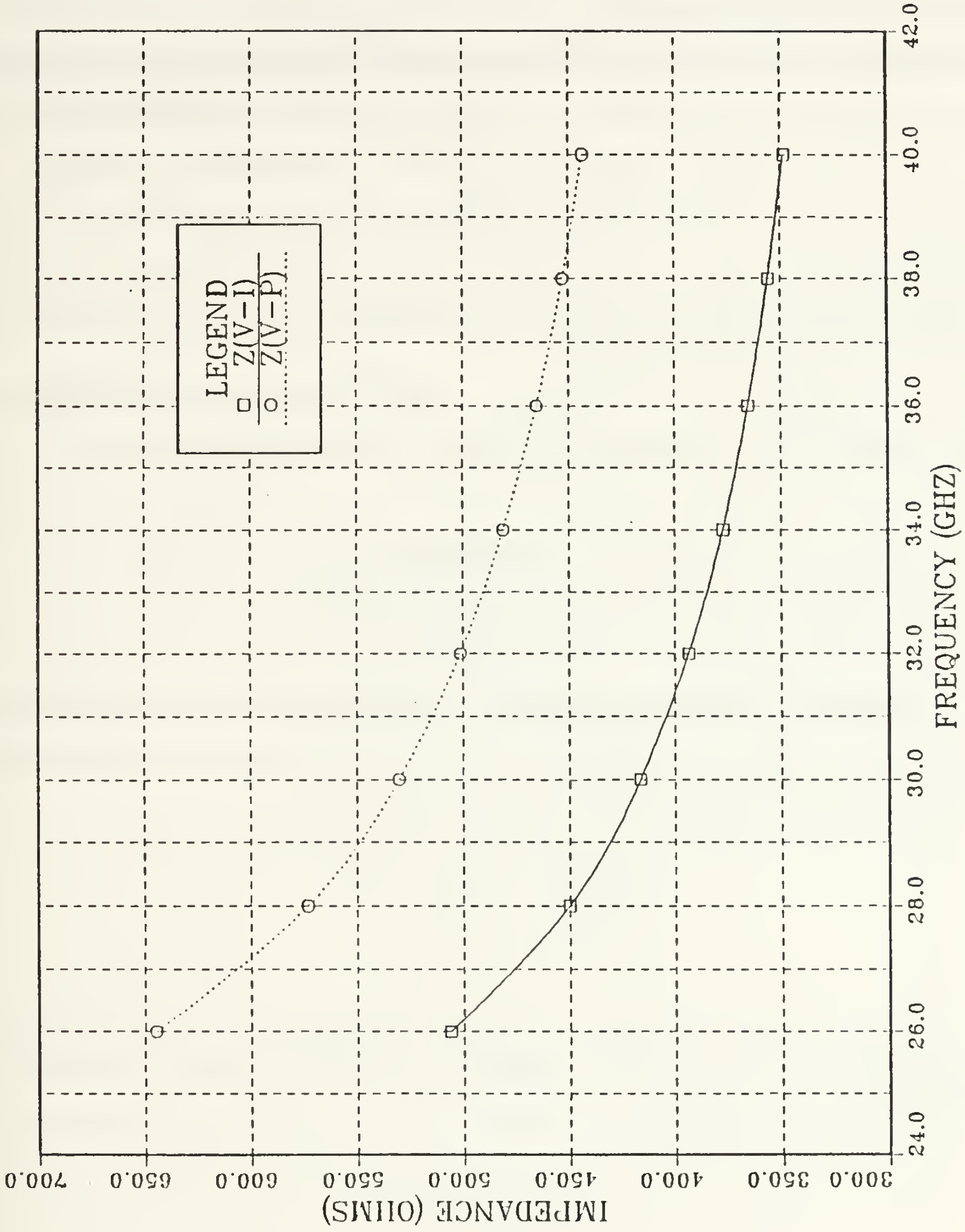

Figure 6. Comparison of impedance definitions, $\frac{w}{b} = 1.00$

III. MODEL CONCEPT

A. HOMOGENEOUS FINLINE

Homogeneous finline is defined as finline uniformly filled with a dielectric material. With $\varepsilon_r = 1$, the structure is identical to a ridged waveguide. It is then possible to establish a simple equivalency between finline and a rectangular waveguide. The waveguide equivalent width is selected to provide the correct wavelength and then the waveguide equivalent height is independently selected to provide the correct impedance. The remainder of this section is devoted to developing the equations for the dimensions of the equivalent rectangular waveguide.

The wavelength within the homogeneous finline is dependent upon the free-space wavelength and the cutoff wavelength of the finline. It can be expressed as:

$$\lambda' = \frac{\lambda_0}{\sqrt{1 - (\frac{\lambda_0}{\lambda_c})^2}} \tag{8}$$

where λ_0 is the free-space wavelength and λ_c is the cutoff wavelength of the finline. Recognizing that the cutoff wavelength for a rectangular waveguide is equal to twice the width of the guide, equation 8 can be rewritten in the form:

$$\frac{\lambda'}{\lambda_0} = \frac{1}{\sqrt{1 - (\frac{\lambda_0}{2a_{eq}})^2}} . \tag{9}$$

Substituting equation 9 into equation 4 results in the following form for the characteristic impedance:

$$Z_{0V} = Z_{0\infty}(\frac{\lambda'}{\lambda_0}). \tag{10}$$

Pramanick and Bhartia [Ref.5: pp. 1437-1438] defined the impedance at infinite frequency based on the capacitance between the midpoints of the waveguide broadwalls. Substituting the equivalent width and height for the finline width and height in this definition yields:

$$Z_{0\infty} = \frac{2b_{eq}}{a_{eq}} \eta_0 \tag{11}$$

where η_0 is the intrinsic impedance of free space, equal to 377 ohms.

The final voltage-power definition is obtained by substituting equation 11 into equation 10, resulting in:

$$Z_{0V} = \frac{2b_{eq}}{a_{eq}} \eta_0 \left(\frac{\lambda'}{\lambda_0} \right). \tag{12}$$

This equation is used in the model to predict the characteristic impedance of finline.

B. INHOMOGENEOUS FINLINE

Inhomogeneous finline is of the type shown in Figure 1 on page 2. Since the dielectric constant of region 2 is no longer unity, the equivalent rectangular waveguide becomes more complex. A 3-dimensional view of the equivalent rectangular waveguide is shown in Figure 7 on page 14. The dimensions are identical to those described for the homogeneous structure, however the waveguide is now considered filled with a material having an effective dielectric constant, k_{eff}. The wavelength ratio expressed in equation 9 is then modified as:

$$\frac{\lambda'}{\lambda_0} = \frac{1}{\sqrt{k_{eff} - \left(\frac{\lambda_0}{2a_{eq}} \right)^2}} . \tag{13}$$

The effective dielectric constant, equivalent width, and free space wavelength are the only parameters required to predict the finline wavelength ratio. The free-space wavelength is known and the equivalent width model is developed in the next chapter. Solving for k_{eff} in equation 13 and making appropriate substitutions yields:

$$k_{eff} = \left(\frac{\lambda_0}{\lambda'} \right)^2 + \left(\frac{f_c}{f} \right)^2 \tag{14}$$

where f is the operational frequency and f_c is the cutoff frequency of the finline structure. All of the tools are now present for the development of the finline model.

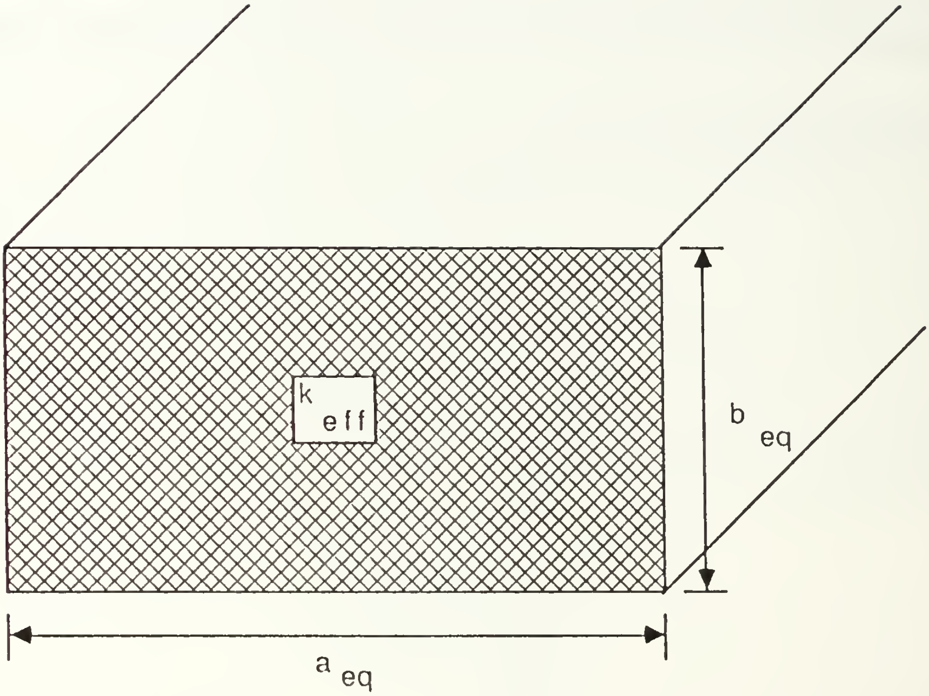

Figure 7. 3-Dimensional view of an equivalent rectangular waveguide

IV. MODEL DEVELOPMENT

A. PRELIMINARY MODEL

The first step in the development process was to determine a relationship for the equivalent width and height. The equivalent width is based on the relation:

$$\frac{a_{eq}}{a} = \frac{2a_{eq}}{2a} = \frac{\lambda_{cf}}{\lambda_{cg}} \tag{15}$$

where λ_{cf} and λ_{cg} are the cutoff wavelengths of the finline and rectangular waveguide structures, respectively. The resulting equivalent width expression is:

$$\frac{a_{eq}}{a} = \frac{\lambda_{cf}}{2a}\,. \tag{16}$$

Algebraic manipulation of equation 12 yields the following expression for equivalent height:

$$\frac{b_{eq}}{b} = \left(\frac{Z_{0\infty}}{\eta_0}\right)\left(\frac{a_{eq}}{a}\right)\left(\frac{a}{2b}\right). \tag{17}$$

These two equations provide the foundation for the preliminary model.

Values of $\frac{a_{eq}}{a}$ for each value of $\frac{w}{b}$ are calculated based on the appropriate cutoff wavelengths of the finline structure. These cutoff wavelengths were computed using spectral domain data. A plot of $\frac{a_{eq}}{a}$ *versus* $\frac{w}{b}$ is shown in Figure 8 on page 20. The curve is a best fit to the data points.

A plot of $\frac{b_{eq}}{b}$ *versus* $\frac{w}{b}$ is shown in Figure 9 on page 21. Data points were computed based on the finline characteristic impedance generated from the spectral domain analysis program and the values of a_{eq} calculated above. These data points are also connected by a best fit curve.

The preliminary model is based on Figures 8 and 9. An equation was generated for the best fit curve in each of these figures. The resulting preliminary model for finline is:

$$\frac{a_{eq}}{a} = 2 - \left\{\left[\left(\frac{w}{b}\right) - 1\right]^2\right\}^{\frac{1}{2}} \tag{18}$$

$$\frac{b_{eq}}{b} = 1 + 0.092 \ln(\frac{w}{b}). \qquad (19)$$

Figures 10 through 23 show comparisons between the actual wavelength ratio and the value predicted by the model. The actual data is depicted by curves, generated by the spectral domain program. The model predictions are depicted by data points and were calculated using equation 13. By defining error as:

$$Error = (\frac{|\,Model\ Value - Spectral\ Domain\ Value\,|}{Spectral\ Domain\ Value})100\% \qquad (20)$$

and calculating this error for each data point, it can be seen that the maximum error does not exceed 1%. This is valid for all substrate thicknesses, all fin-gap-to-height ratios, and across the entire Ka frequency band.

A similar comparison was conducted for the characteristic impedance with disappointing results. Although errors were less than 5% for substrate thicknesses of 0 and 5 mils, the errors balooned to over 12% for thicknesses of 25 and 30 mils. These results were considered totally unsatisfactory.

B. OPTIMUM VALUES OF THE EQUIVALENT HEIGHT

Recognizing that equation 18 led to excellent wavelength ratio prediction results, a decision was made to retain this expression as part of the model and concentrate on developing an equivalent height expression which would provide satisfactory results. Although the predicted wavelength ratio is a factor in the impedance prediction expression, analysis showed that the small errors associated with wavelength prediction would not significantly affect the impedance prediction results. This justified the continued utilization of equation 18 as part of the finline model.

A different approach was employed to reduce the error in impedance prediction. For each substrate thickness and fin-gap-to-height ratio, a value of $\frac{b_{eq}}{b}$ was computed which provided minimum error across the Ka band of frequencies. These *optimum* values of $\frac{b_{eq}}{b}$ generally placed the minimum error at the center of the frequency band. Figure 24 shows curves of optimum $\frac{b_{eq}}{b}$ for applicable values of $\frac{D}{a}$. These curves are best fit curves to the computed data points.

A dual implementaion is now possible. First, each curve can be approximated using a polynomial. This results in a model of eight total expressions, including the expression for $\frac{a_{eq}}{a}$. The second approach is to find one expression containing a correction for $\frac{D}{a}$.

resulting in a model of only two equations. The next section is devoted to discussing the first implementation. The second implementation is discussed in the last section of this Chapter.

C. MODEL VERSION I

As stated in the previous section, Version I involves finding a ploynomial expression for each of the curves in Figure 24. A fifth-order polynomial was selected which provided best fit accuracies greater than 98%. The final model of Version I, with equation 18 included for completeness, is:

$$\frac{a_{eq}}{a} = 2 - \{[(\frac{w}{b}) - 1]^2\}^{\frac{1}{2}} \tag{21}$$

for $\frac{D}{a} = 0$

$$\frac{b_{eq}}{b} = 155.2710(\frac{w}{b})^5 - 292.8609(\frac{w}{b})^4 + 175.9843(\frac{w}{b})^3 - 43.4344(\frac{w}{b})^2 + 5.5435(\frac{w}{b}) + 0.4966 \tag{22}$$

for $\frac{D}{a} = 0.0179$

$$\frac{b_{eq}}{b} = 182.6308(\frac{w}{b})^5 - 344.4615(\frac{w}{b})^4 + 206.7293(\frac{w}{b})^3 - 50.6477(\frac{w}{b})^2 + 6.2715(\frac{w}{b}) + 0.5256 \tag{23}$$

for $\frac{D}{a} = 0.0357$

$$\frac{b_{eq}}{b} = 160.6912(\frac{w}{b})^5 - 306.4514(\frac{w}{b})^4 + 188.0189(\frac{w}{b})^3 - 48.0644(\frac{w}{b})^2 + 6.3727(\frac{w}{b}) + 0.5270 \tag{24}$$

for $\frac{D}{a} = 0.0536$

$$\frac{b_{eq}}{b} = 173.5666(\frac{w}{b})^5 - 328.6663(\frac{w}{b})^4 + 198.8627(\frac{w}{b})^3 - 49.6504(\frac{w}{b})^2 + 6.4915(\frac{w}{b}) + 0.5257 \tag{25}$$

for $\frac{D}{a} = 0.0714$

$$\frac{b_{eq}}{b} = 179.3711(\frac{w}{b})^5 - 338.4721(\frac{w}{b})^4 + 203.3727(\frac{w}{b})^3 - 50.1473(\frac{w}{b})^2 + 6.5023(\frac{w}{b}) + 0.5240 \tag{26}$$

for $\frac{D}{a} = 0.0893$

$$\frac{b_{eq}}{b} = 175.0917(\frac{w}{b})^5 - 330.8076(\frac{w}{b})^4 + 199.2296(\frac{w}{b})^3 - 49.3260(\frac{w}{b})^2 + 6.4622(\frac{w}{b}) + 0.5216 \tag{27}$$

for $\frac{D}{a} = 0.1071$

$$\frac{b_{eq}}{b} = 168.1895(\frac{w}{b})^5 - 318.3413(\frac{w}{b})^4 + 192.4076(\frac{w}{b})^3 - 47.9505(\frac{w}{b})^2 + 6.3492(\frac{w}{b}) + 0.5200 \, . \tag{28}$$

The simplicity of this version is that it incorporates only one variable parameter of the finline structure. The fin gap width is normalized with respect to the finline height.

Figures 25 through 38 show comparisons between the actual characteristic impedance and the value predicted by the model. The actual data are depicted by curves generated from the spectral domain analysis program. The model predictions are depicted by data points and were calculated using equation 12. The definition of error is the same as expressed in equation 20. Examining this error for all substrate thicknesses and fin-gap-to-height ratios, it can be seen that the maximum impedance error does not exceed 5.4%. The majority of this error is associated with the optimization process discussed in the previous section. The curve fitting process used in this implementation increases that error by less than 1%.

D. MODEL VERSION II

The results of Version I were considered acceptable in view of the inherent error associated with the optimization process. The original model concept envisioned utilizing only two equations, one for the equivalent width and one for the equivalent height. It was therefore necessary to go back to Figure 24 and attempt to find an expression which best fit all seven curves. A fifth-order polynomial was again selected as a base expression. A modifying factor was then sought to compensate for the variable substrate thickness. An exhaustive search for this modifying factor eventually yielded the exponential expression $\exp(\frac{D}{a})$. The model for Version II, again with equation 18 included for completeness, is:

$$\frac{a_{eq}}{a} = 2 - \{[(\frac{w}{b}) - 1]^2\}^{\frac{1}{2}} \tag{29}$$

$$\frac{b_{eq}}{b} = [177.4987(\frac{w}{b})^5 - 333.9903(\frac{w}{b})^4 + 199.3337(\frac{w}{b})^3 - 48.3122(\frac{w}{b})^2 + 6.0349(\frac{w}{b}) + 0.4910] \exp(\frac{D}{a}) \tag{30}$$

where $\frac{D}{a} \leq 0.1071$. This version of the model incorporates two of the variable parameters of the finline structure while at the same time retaining a relativly simple form.

Figures 39 through 52 show comparisons between the model impedance and that predicted using the spectral domain technique. As was the case with the impedance figures of the previous section, the curves are plots of the spectral domain data while the model data is depicted by data points, calculated using equation 12. The error definition remains unchanged. Analysis of the impedance errors for Version II reveals a maximum error of less than 7%. The consolidation of all $\frac{b_{eq}}{b}$ curves into one expression has increased the maximum error by only 1.5%.

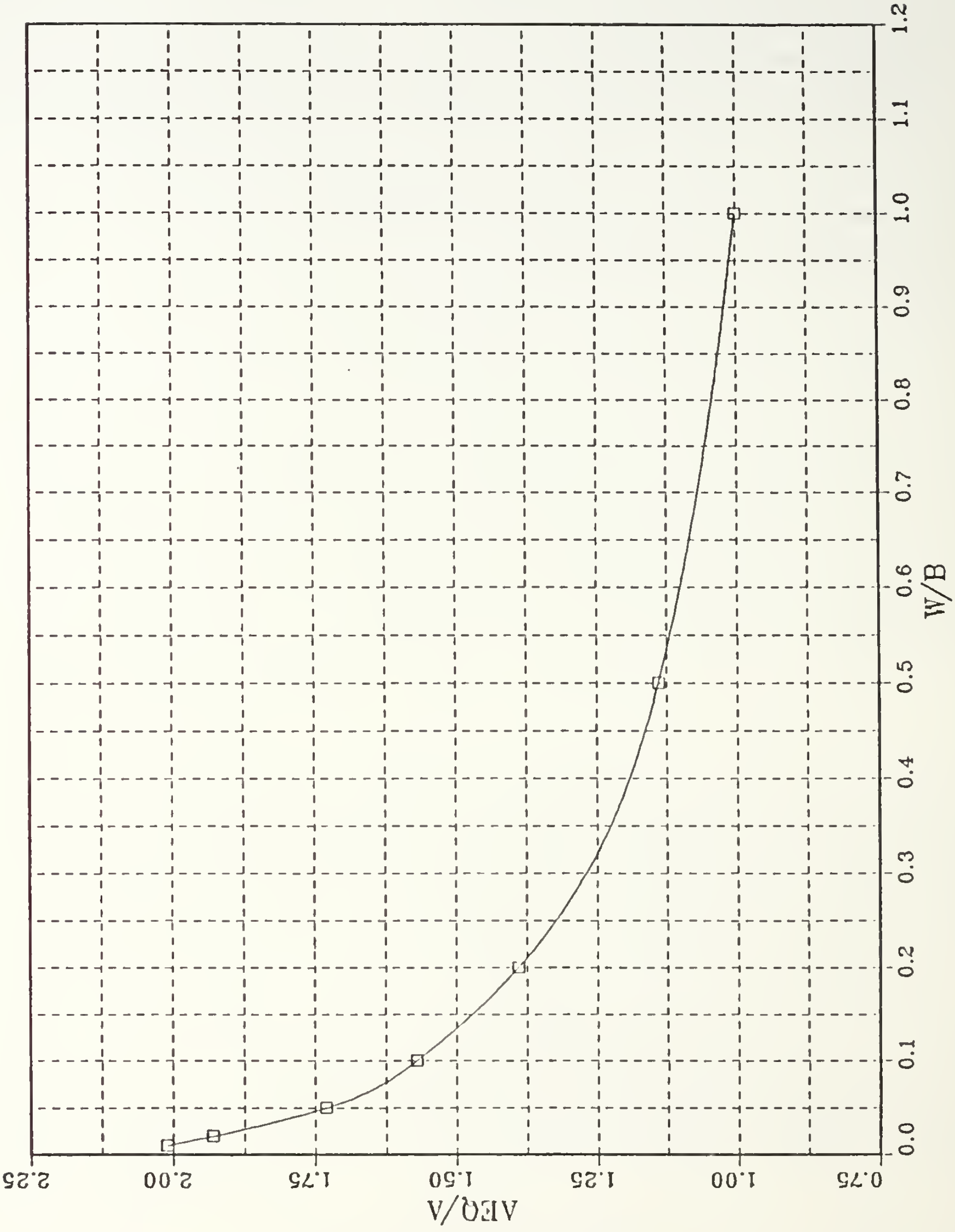

Figure 8. Graph of $\frac{a_{eq}}{a}$ *versus* $\frac{w}{b}$

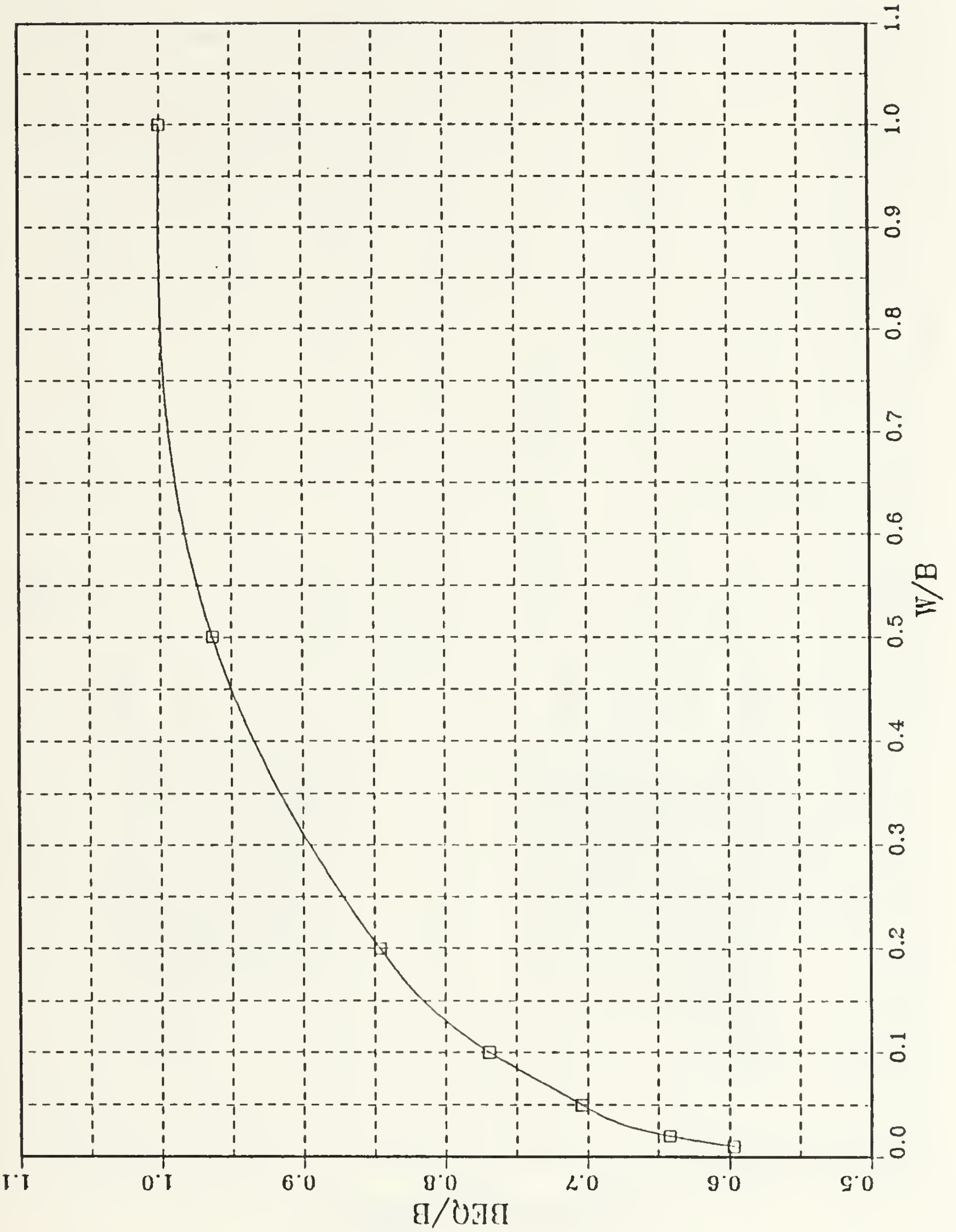

Figure 9. Graph of $\frac{b_{eq}}{b}$ *versus* $\frac{w}{b}$

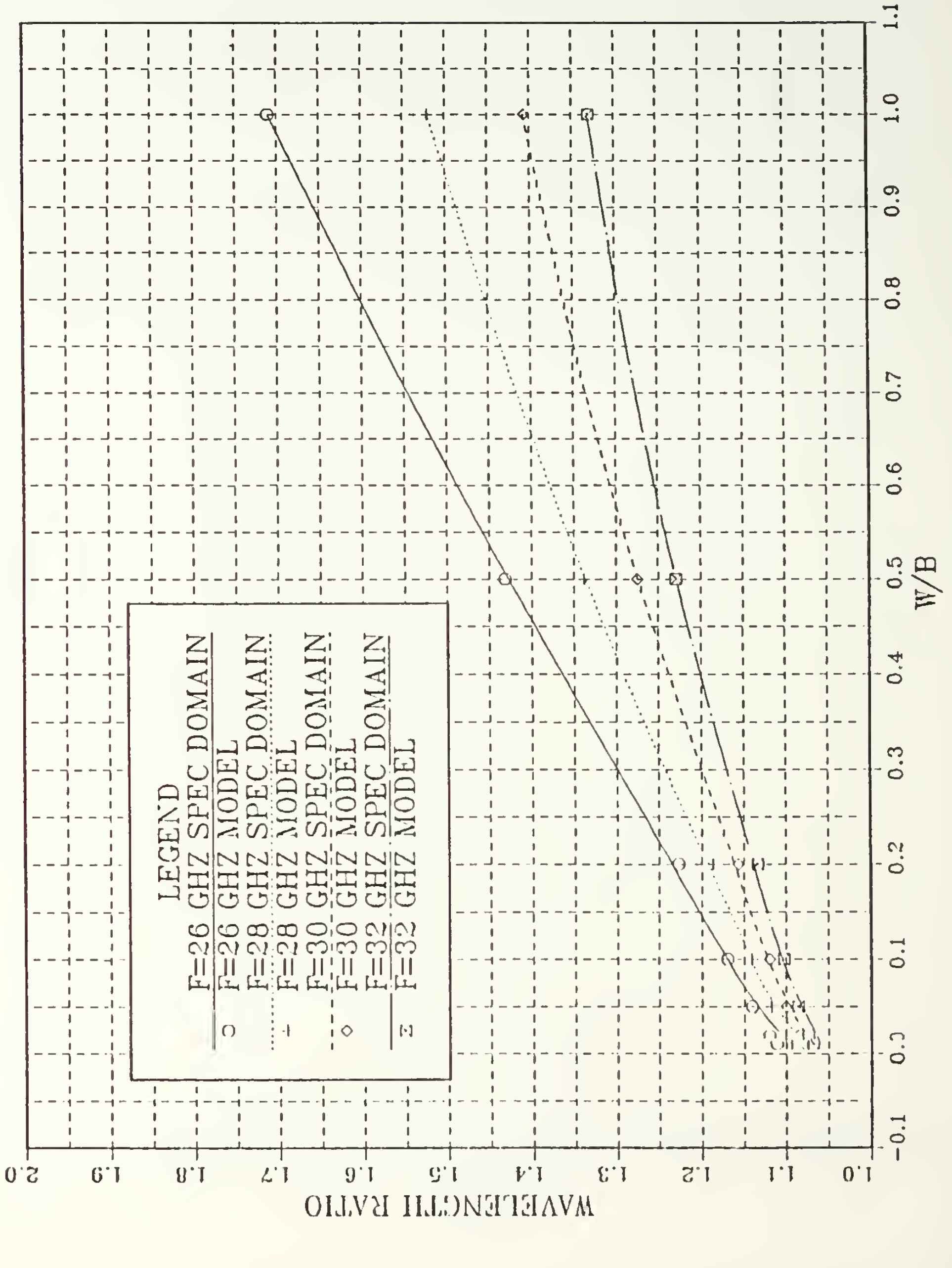

Figure 10. Wavelength prediction results for $\frac{D}{a}$ =0, 26-32 GHz.

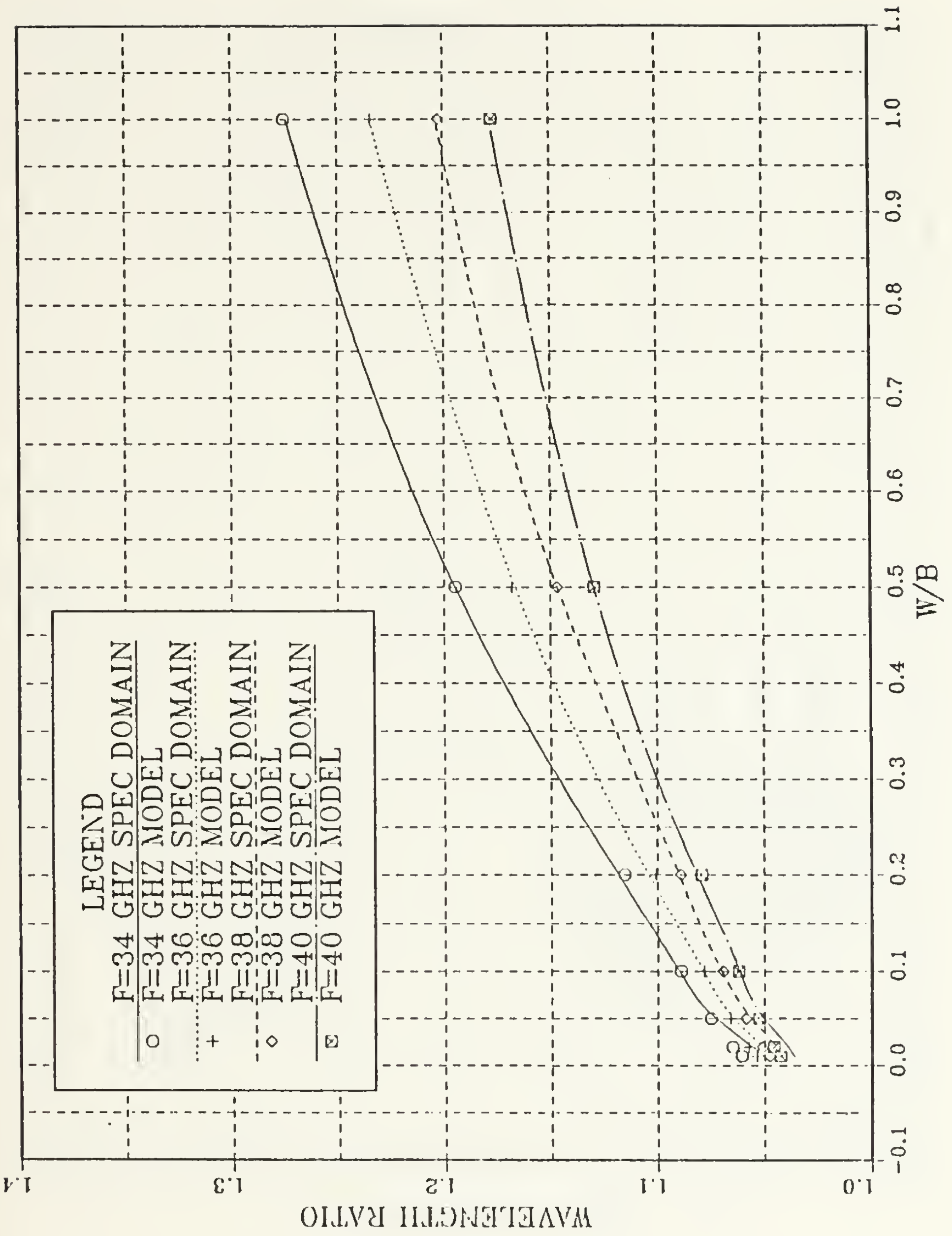

Figure 11. Wavelength prediction results for $\frac{D}{a}=0$, 34-40 GHz.

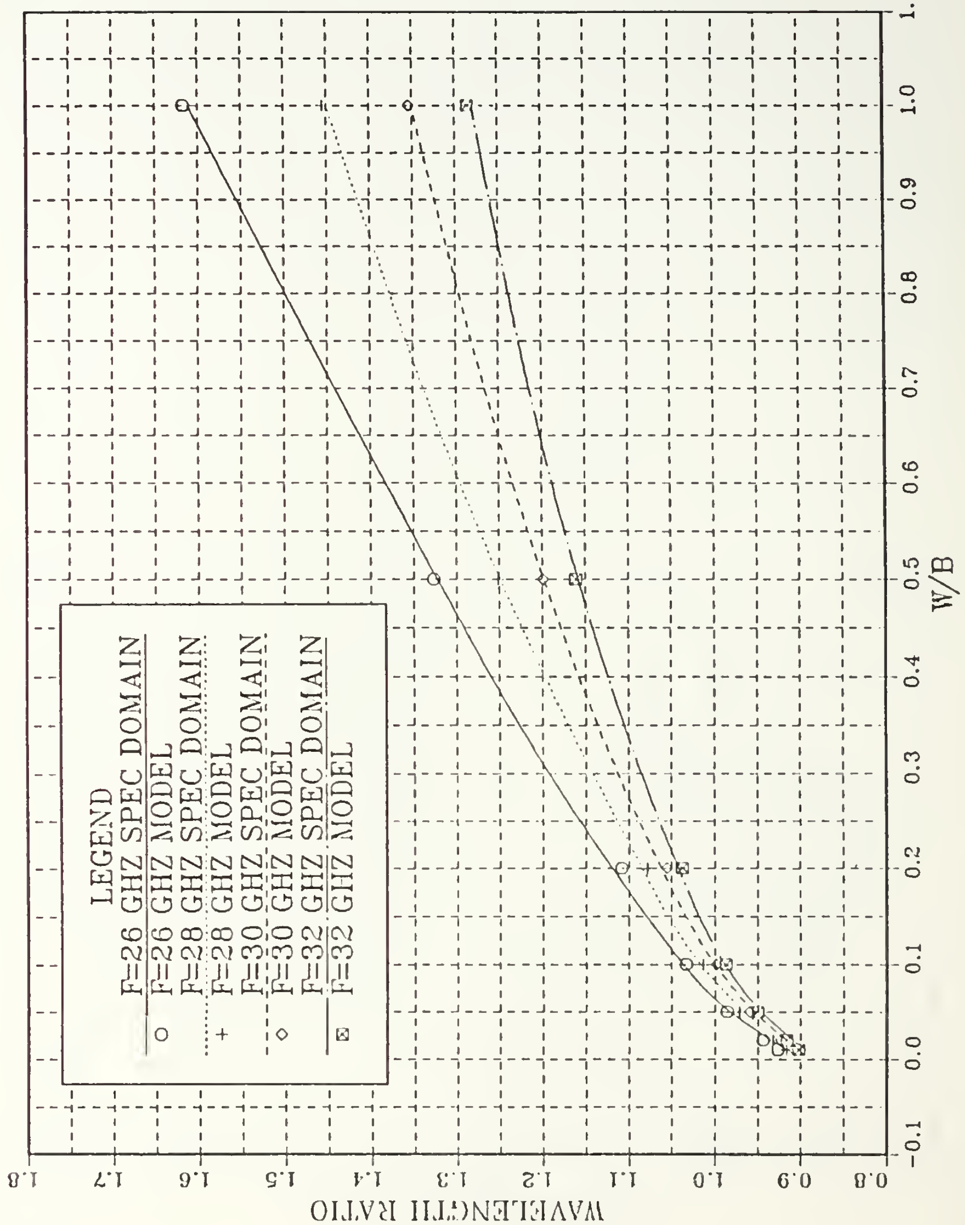

Figure 12. Wavelength prediction results for $\frac{D}{a}$ =0.0179, 26-32 GHz.

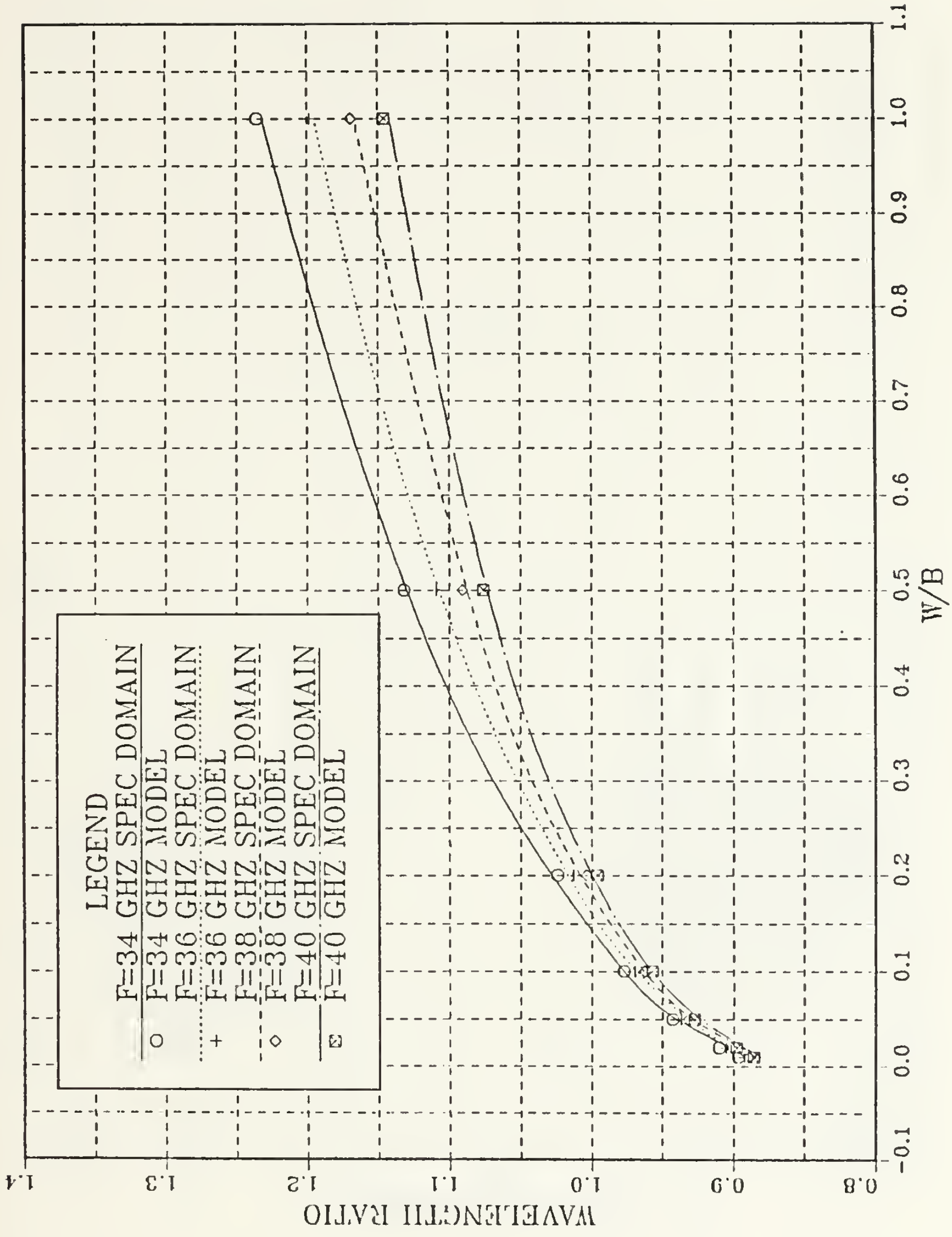

Figure 13. Wavelength prediction results for $\frac{D}{a}$ =0.0179, 34-40 GHz.

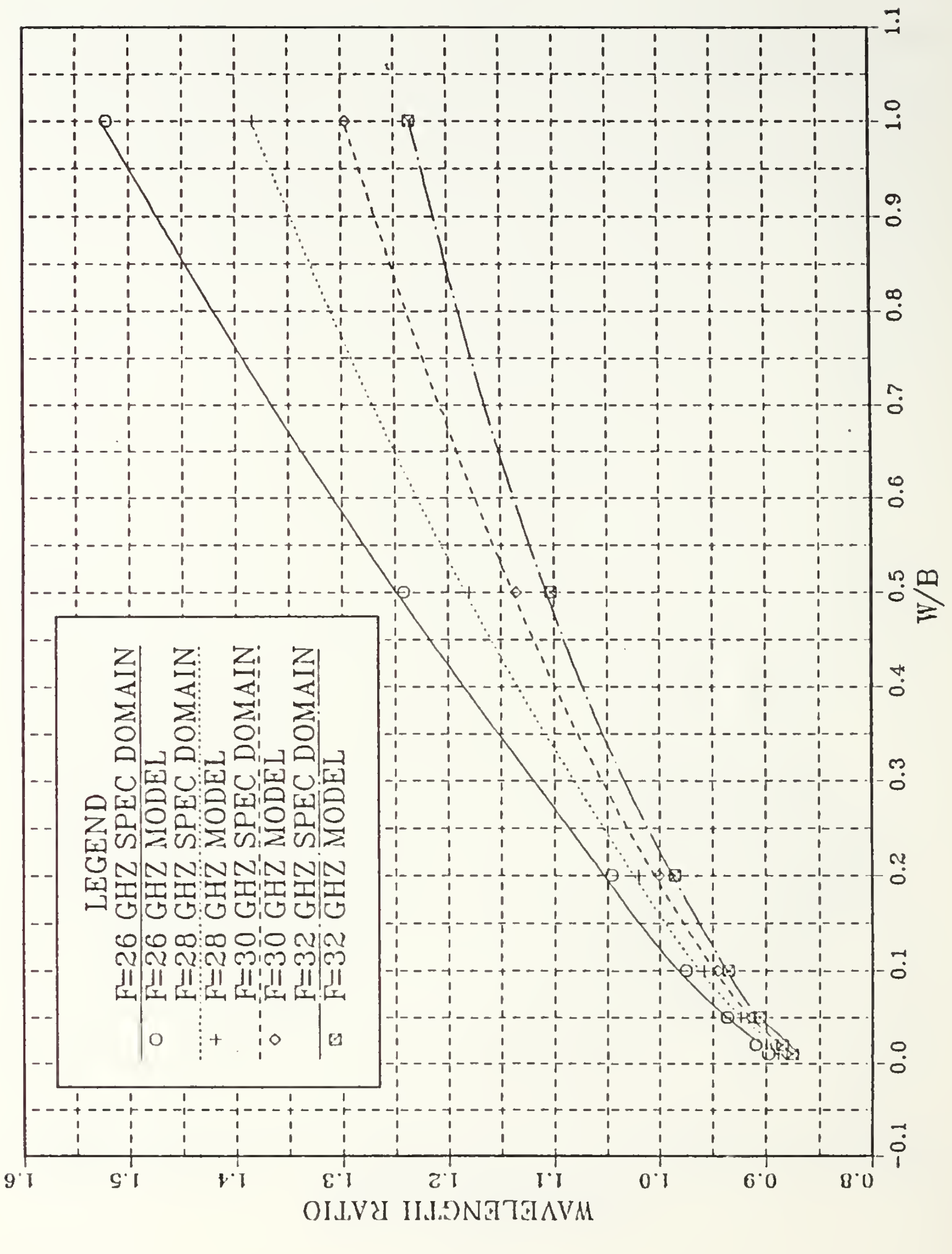

Figure 14. Wavelength prediction results for $\frac{D}{a}$ =0.0357, 26-32 GHz.

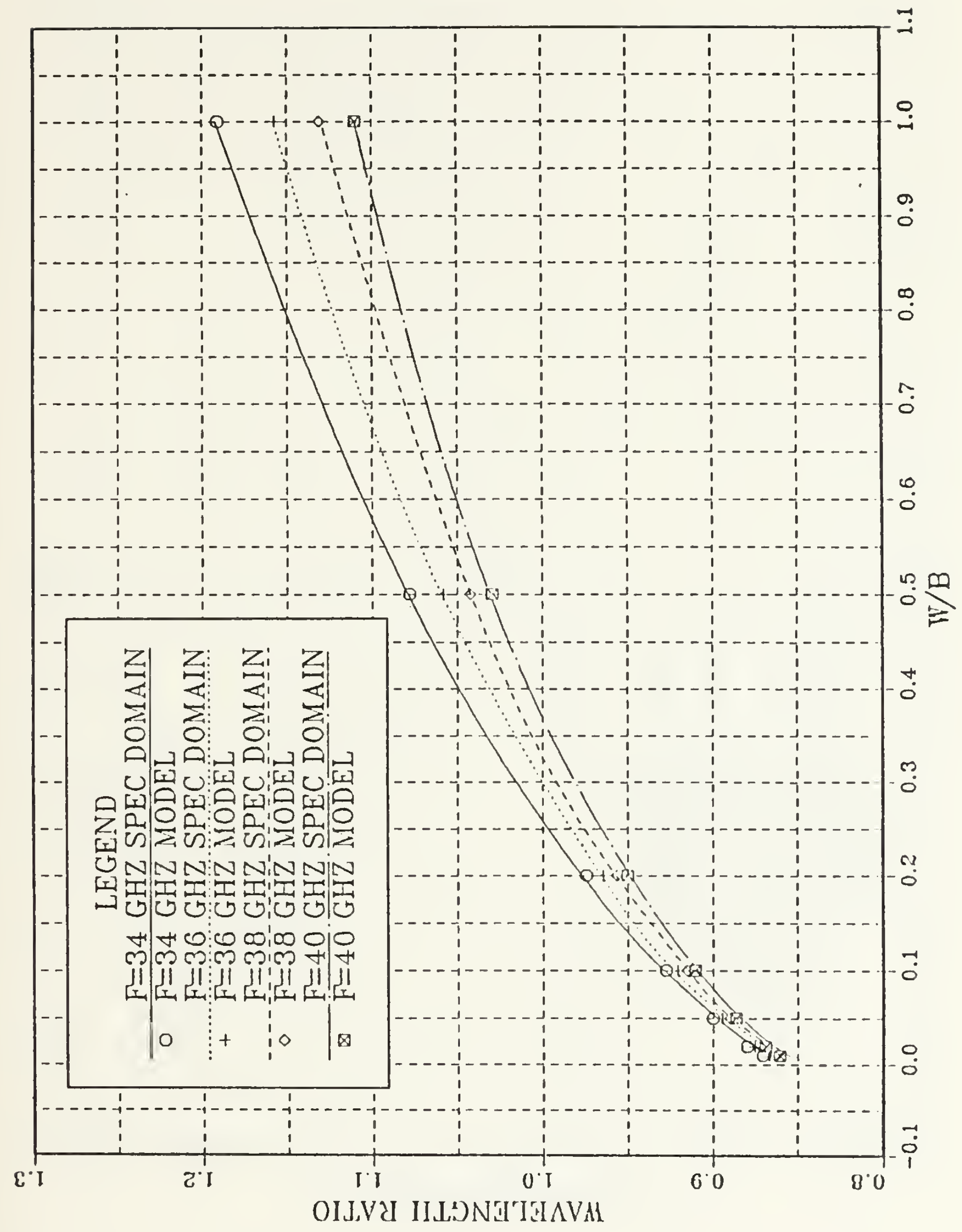

Figure 15. Wavelength prediction results for $\frac{D}{a}$ =0.0357, 34-40 GHz.

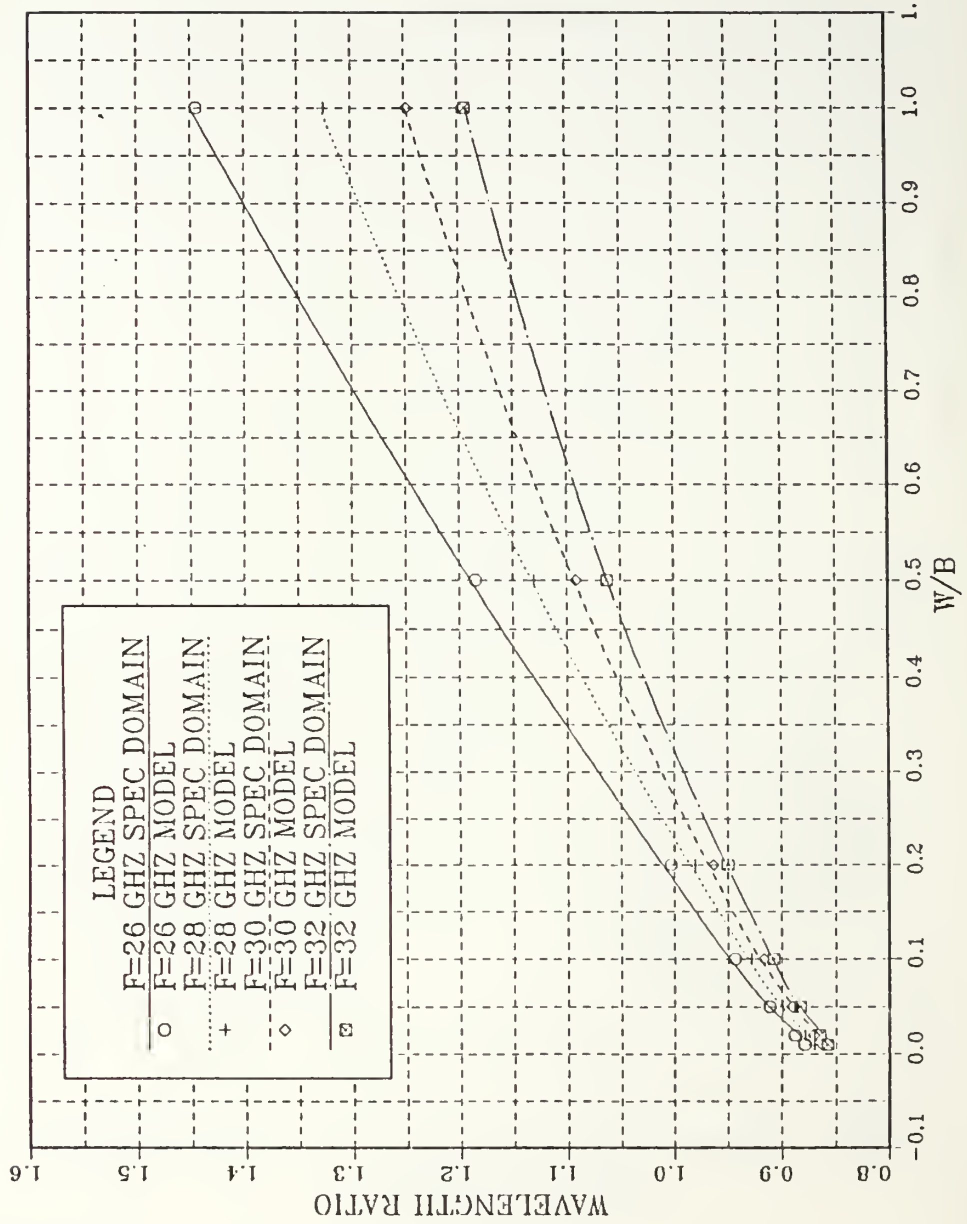

Figure 16. Wavelength prediction results for $\frac{D}{a}$ =0.0536, 26-32 GHz.

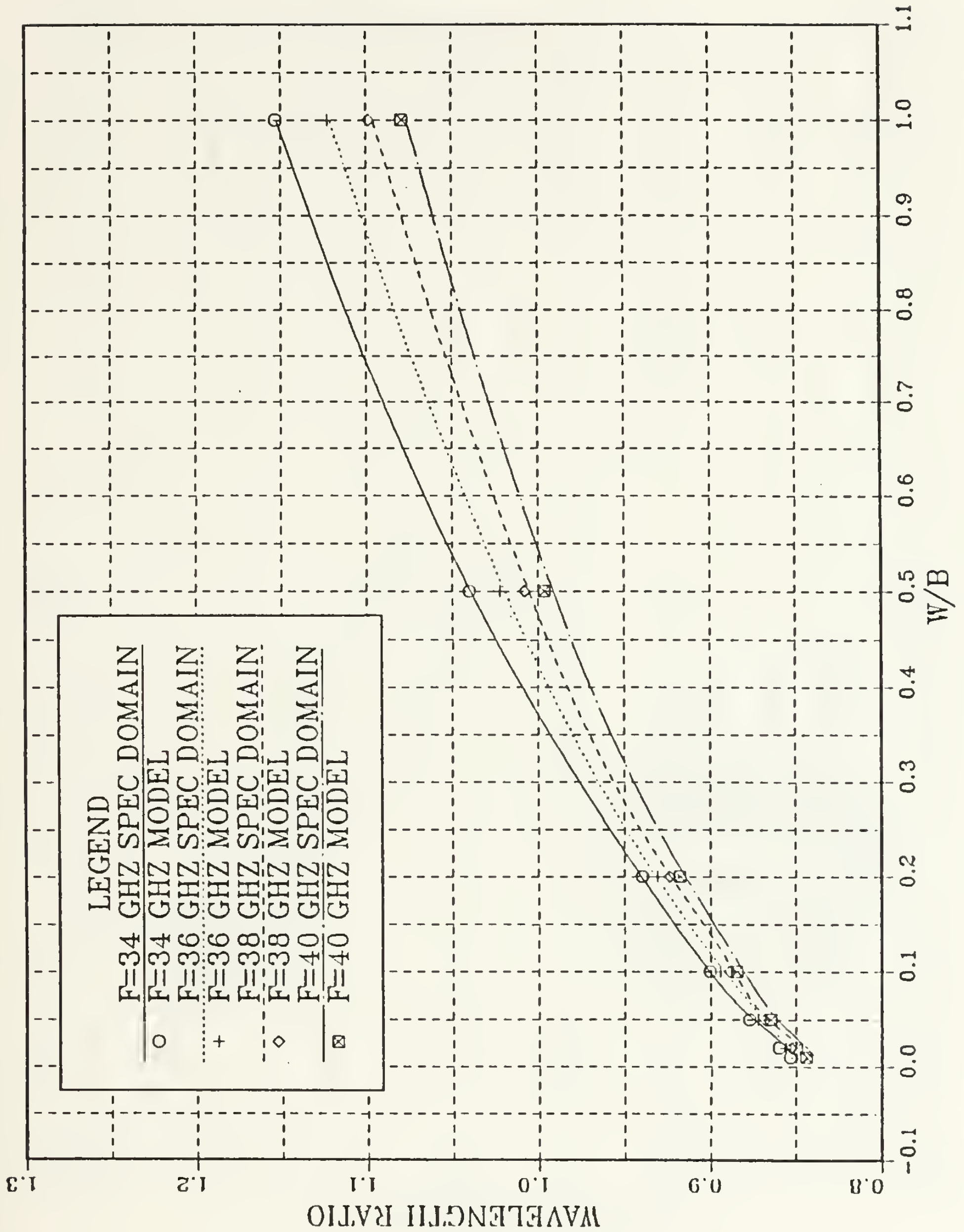

Figure 17. Wavelength prediction results for $\frac{D}{a}$ =0.0536, 34-40 GHz.

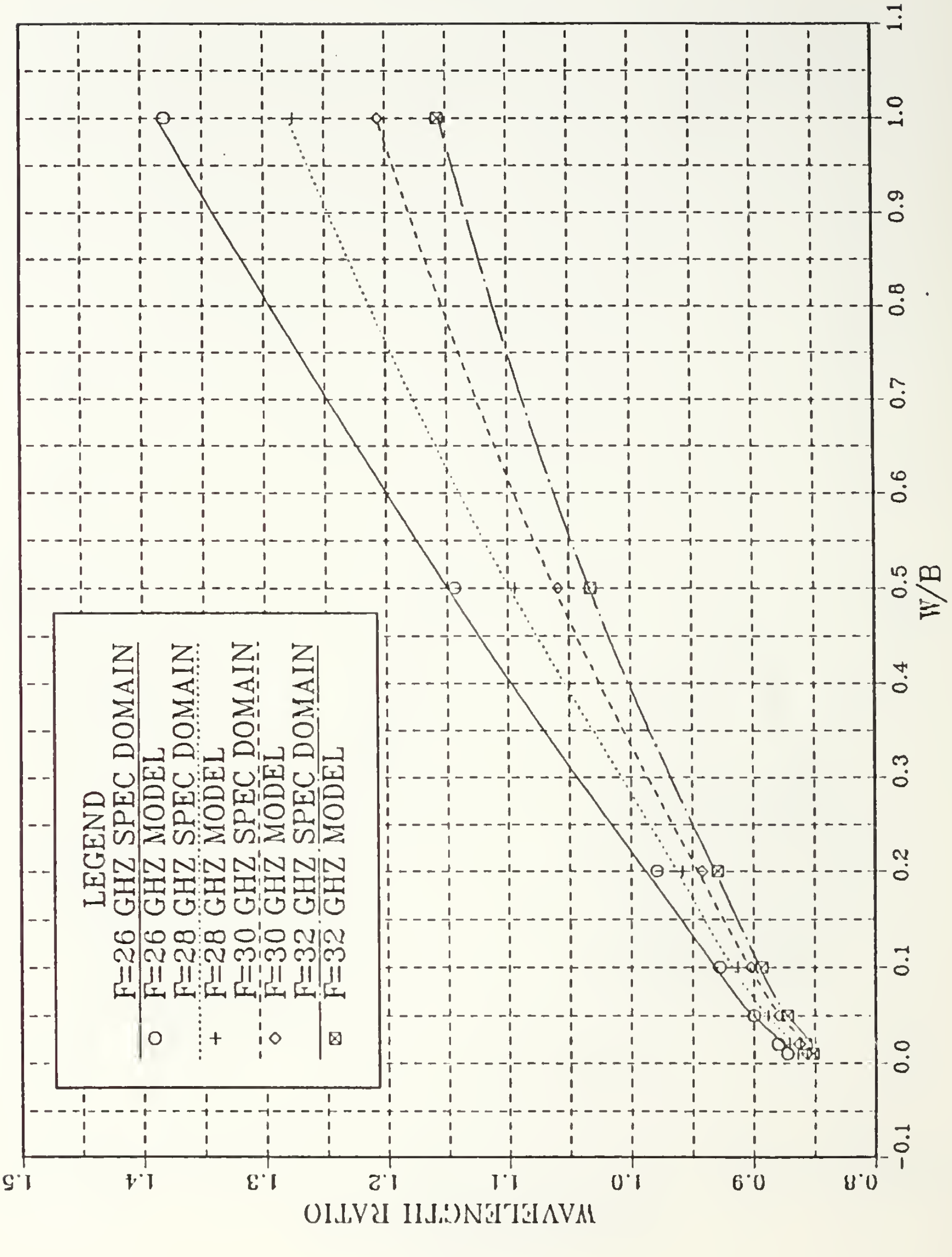

Figure 18. Wavelength prediction results for $\frac{D}{a}$ =0.0714, 26-32 GHz.

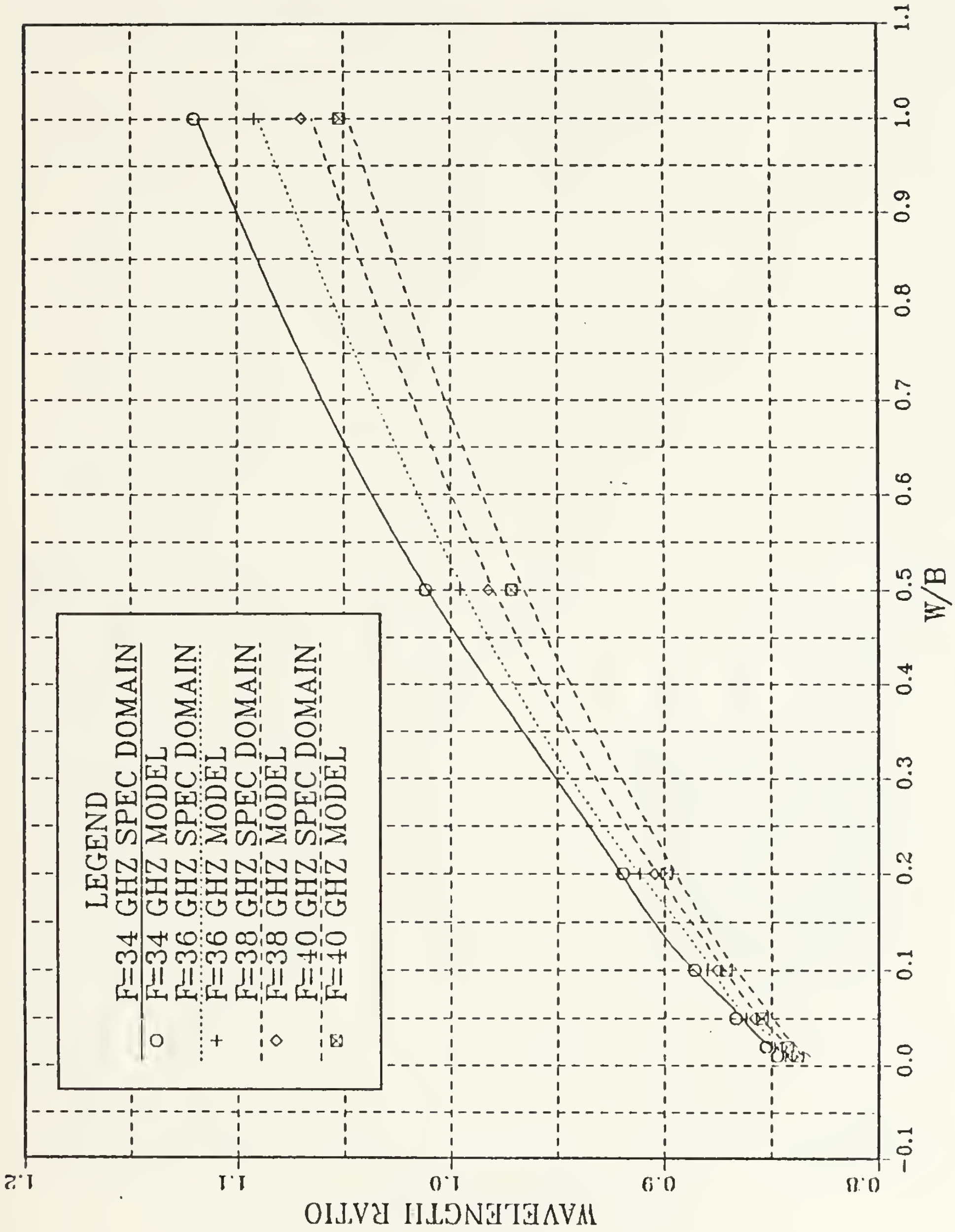

Figure 19. Wavelength prediction results for $\frac{D}{a}$ =0.0714, 34-40 GHz.

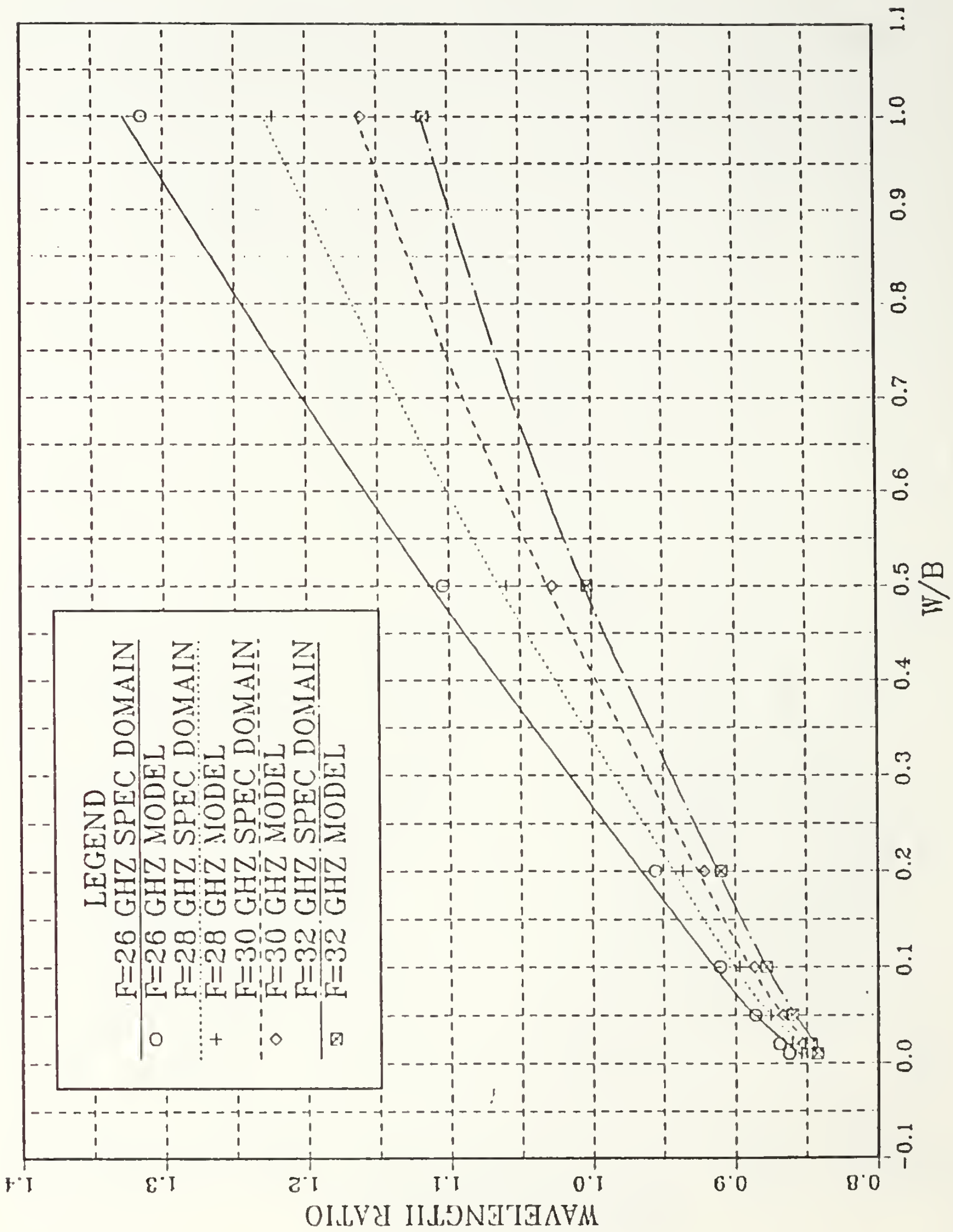

Figure 20. Wavelength prediction results for $\frac{D}{a}$ =0.0893, 26-32 GHz.

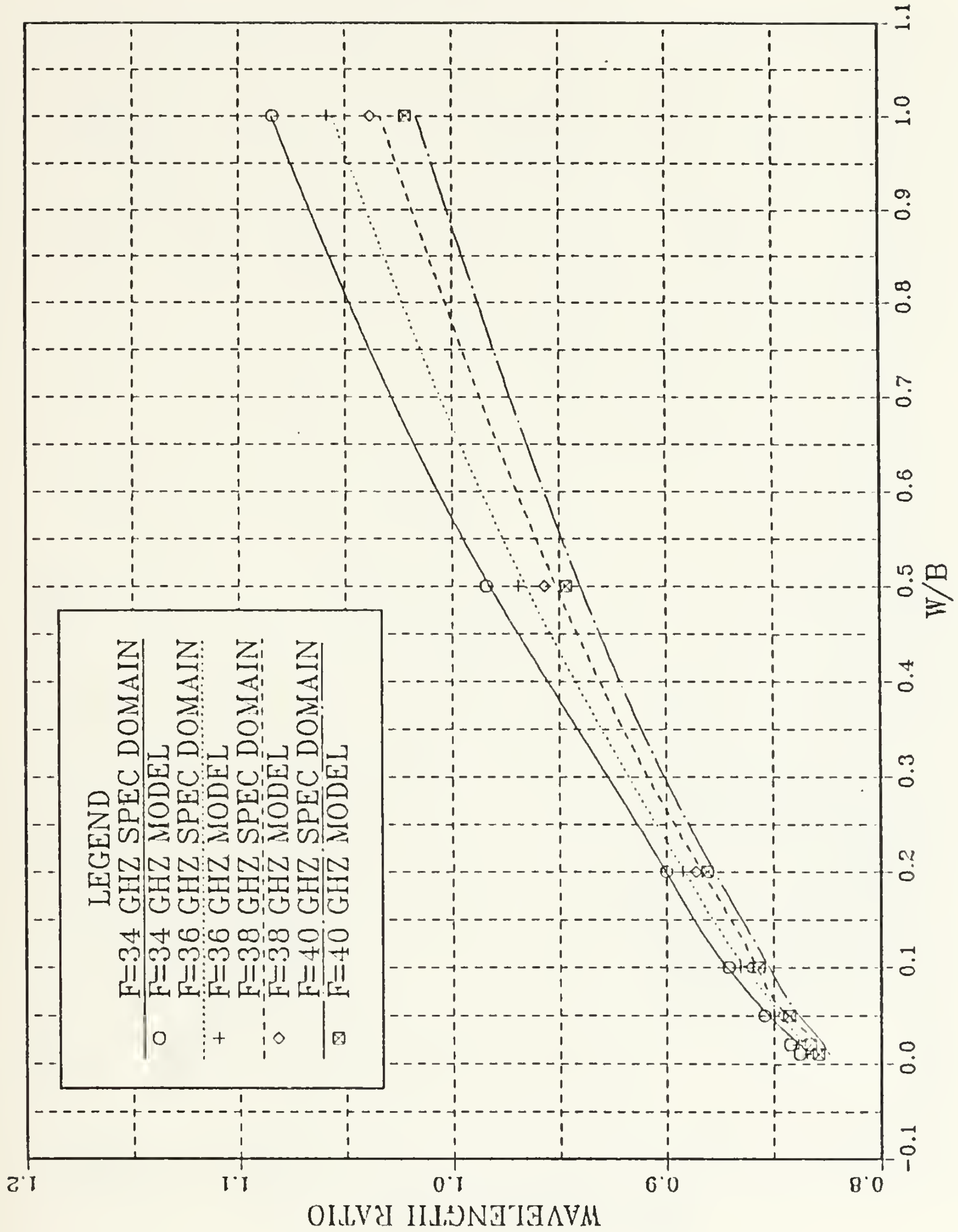

Figure 21. Wavelength prediction results for $\frac{D}{a}$ =0.0893, 34-40 GHz.

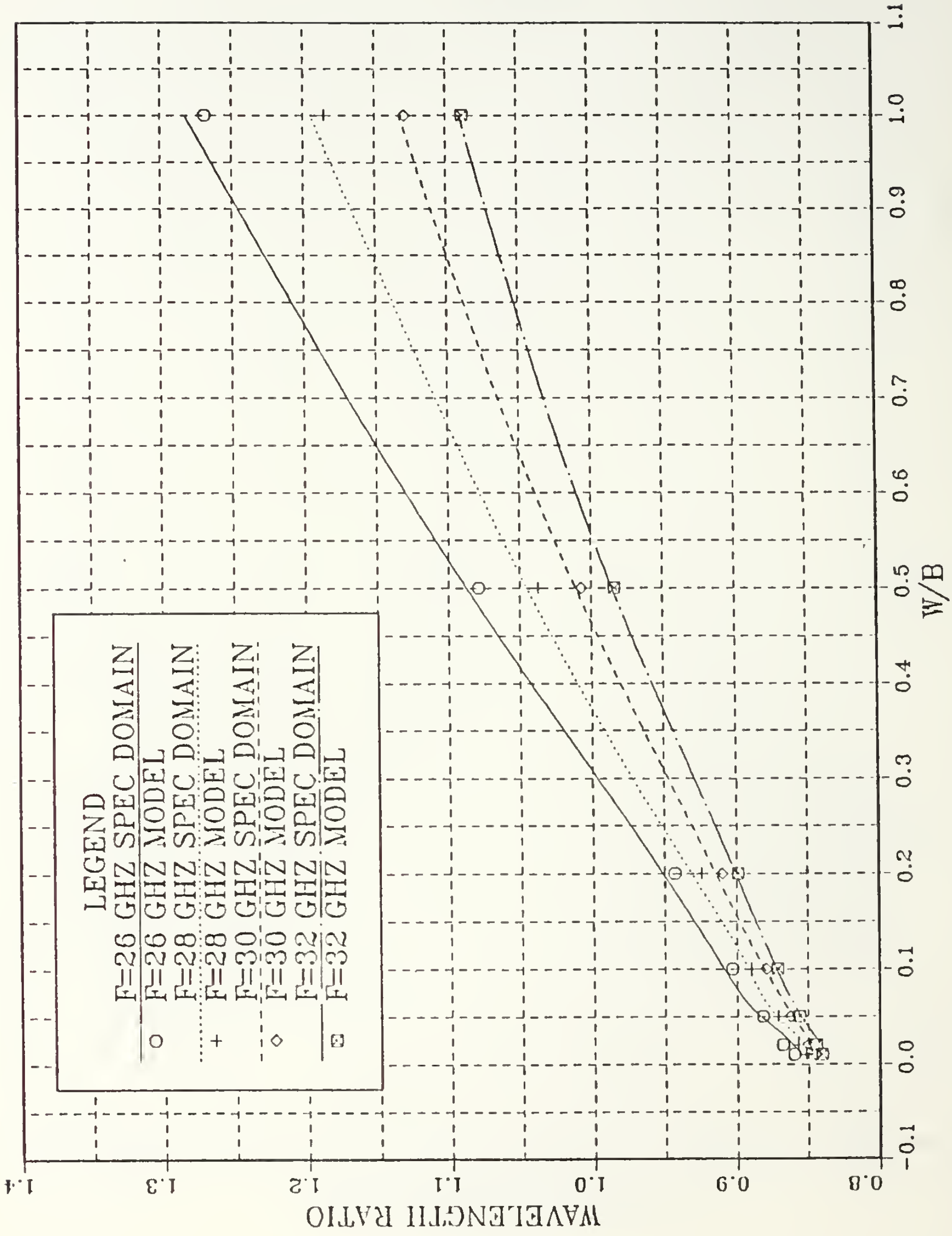

Figure 22. Wavelength prediction results for $\frac{D}{a}$ =0.1071, 26-32 GHz.

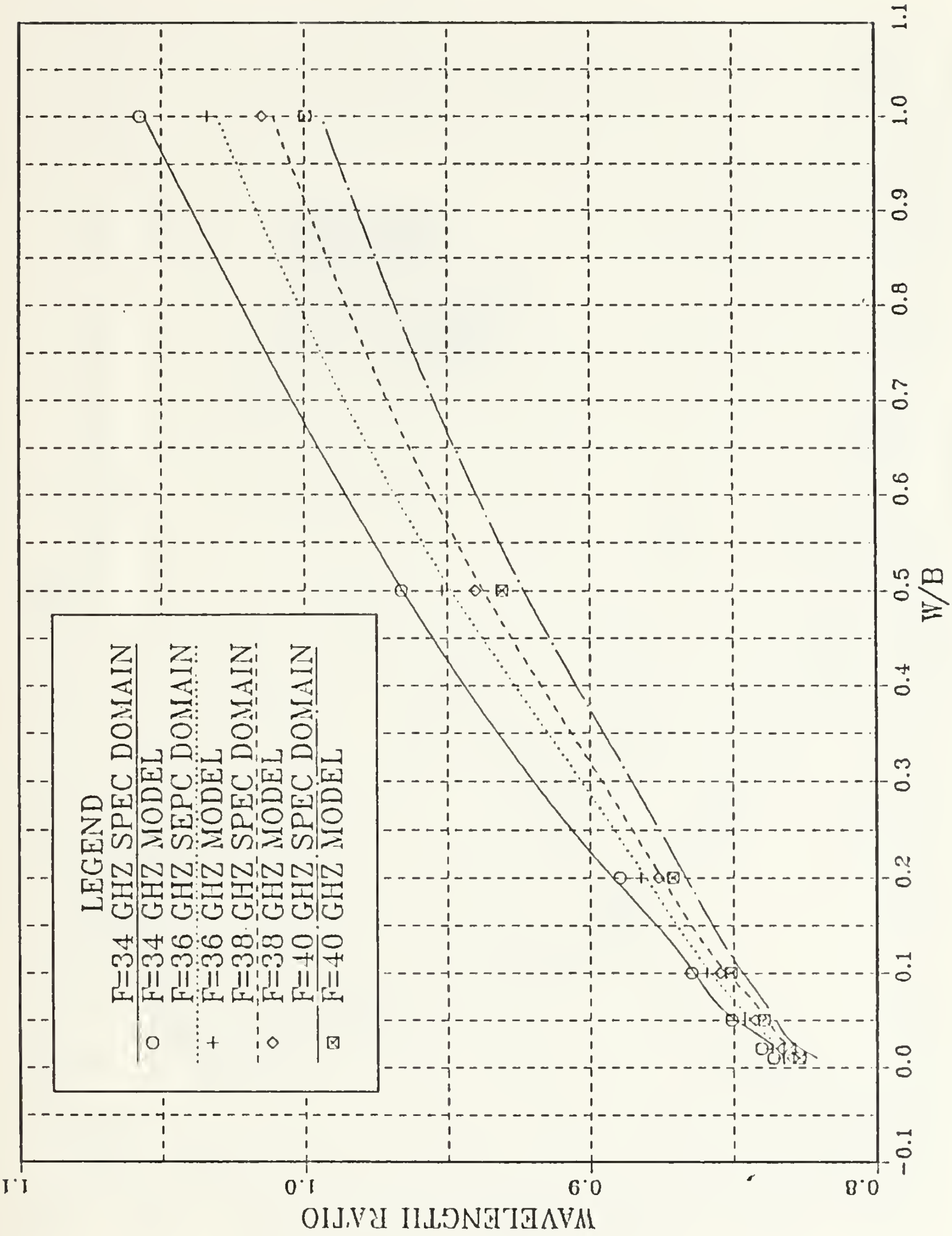

Figure 23. Wavelength prediction results for $\frac{D}{a}$ =0.1071, 34-40 GHz.

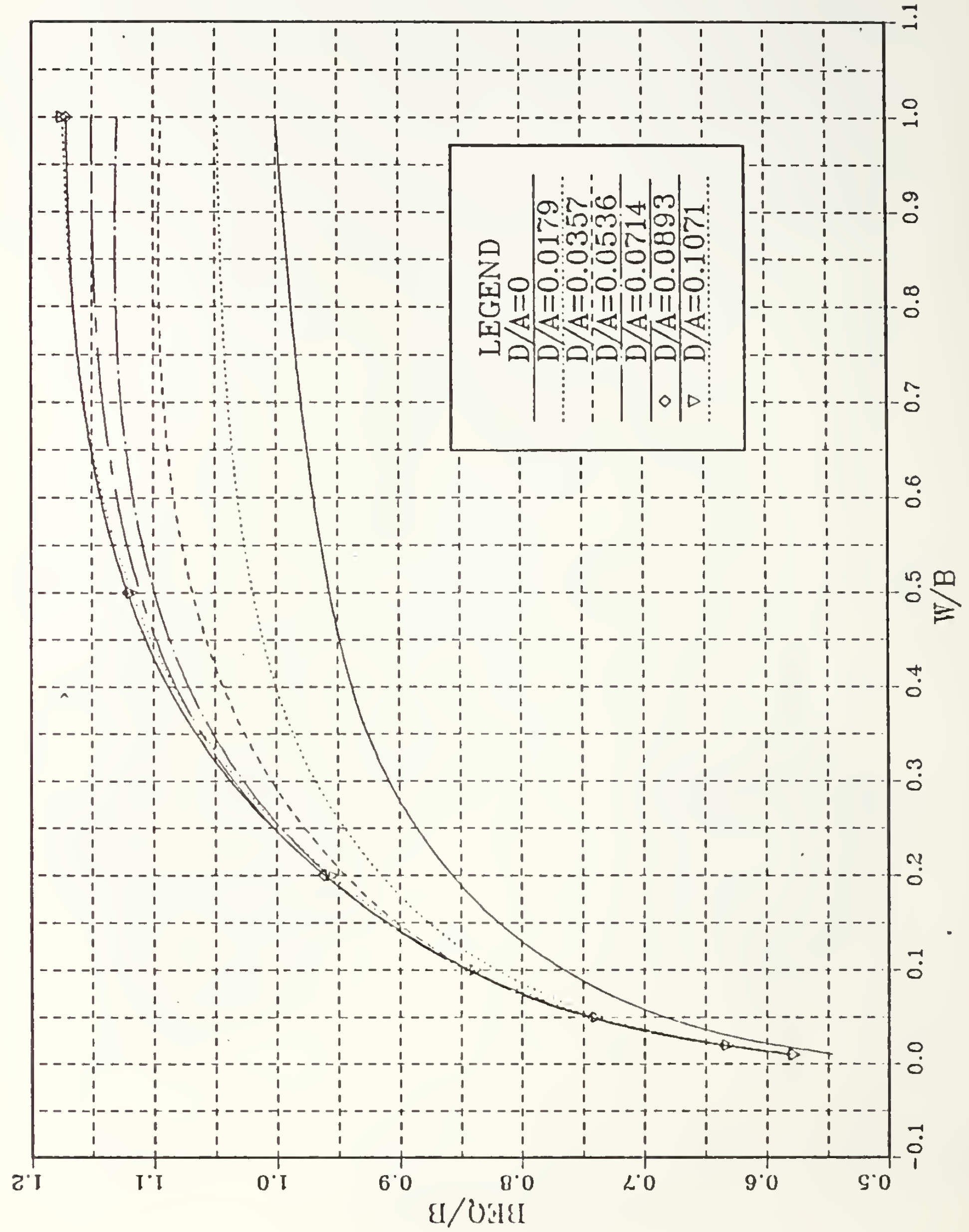

Figure 24. Curves of $\frac{b_{eq}}{b}$ for applicable $\frac{D}{a}$.

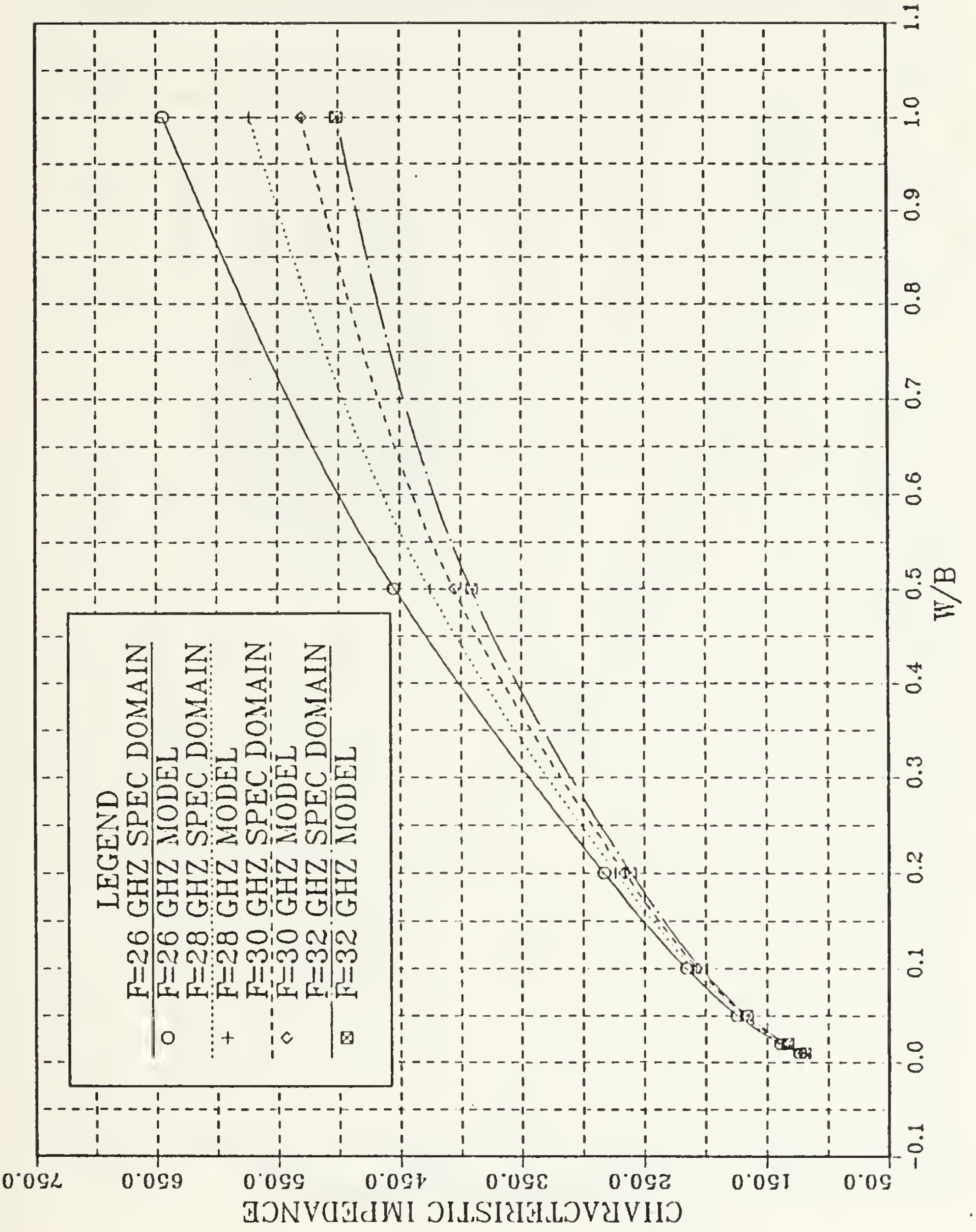

Figure 25. Impedance prediction results for Version I, $\frac{D}{a}=0$, 26-32 GHz.

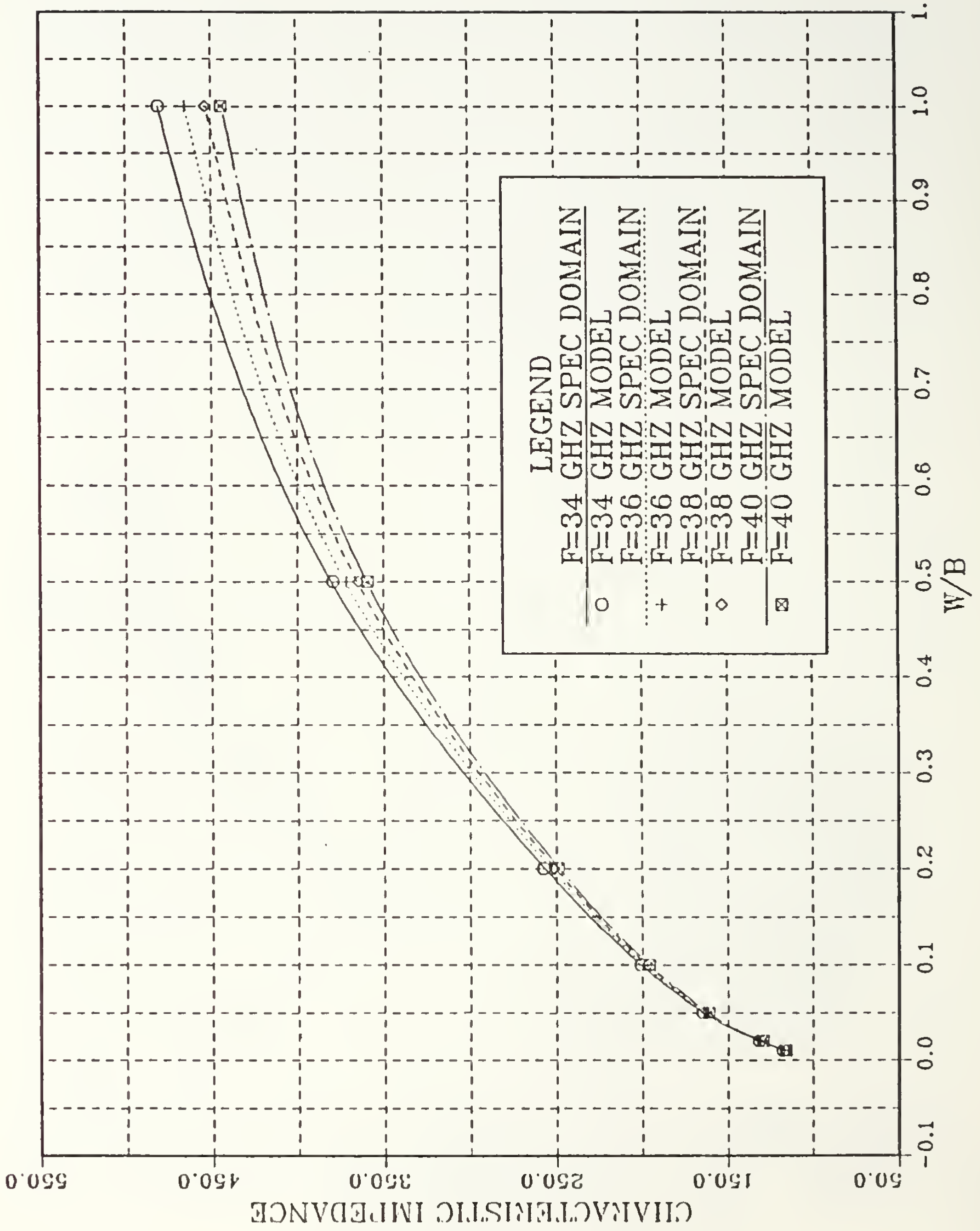

Figure 26. Impedance prediction results for Version I, $\frac{D}{a}$ =0, 34-40 GHz.

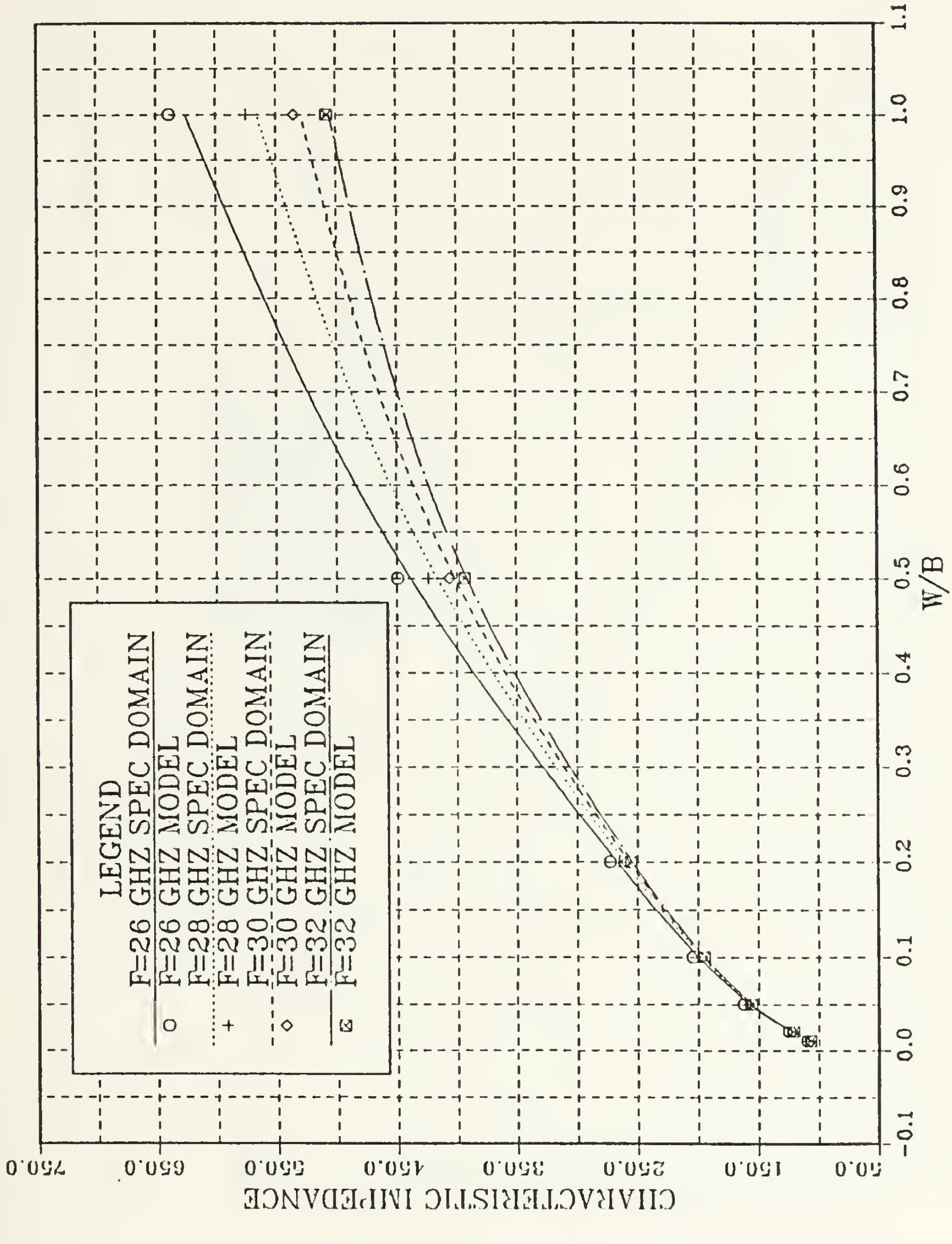

Figure 27. Impedance prediction results for Version I, $\frac{D}{a}$ =0.0179, 26-32 GHz.

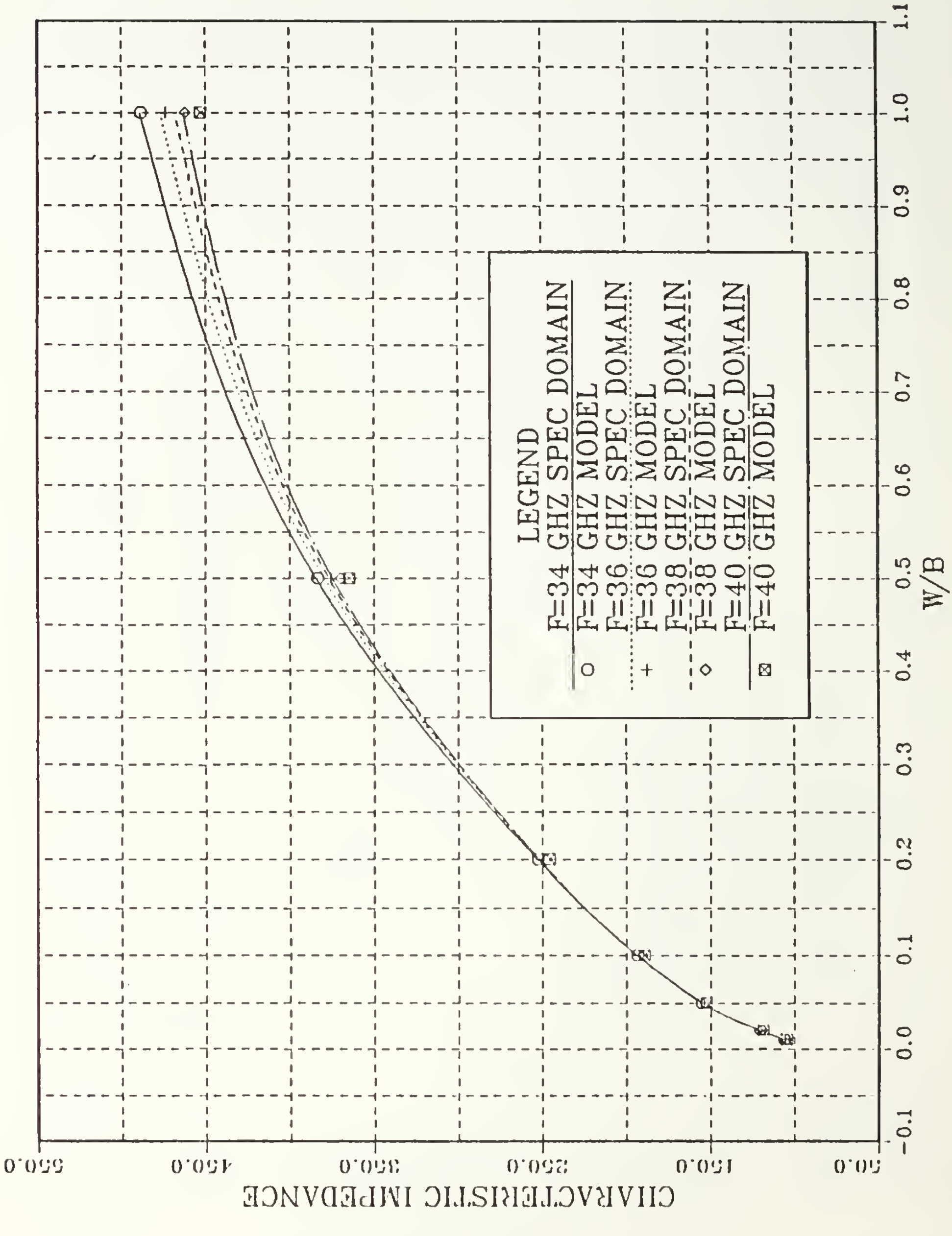

Figure 28. Impedance prediction results for Version I, $\frac{D}{a}$ =0.0179, 34-40 GHz.

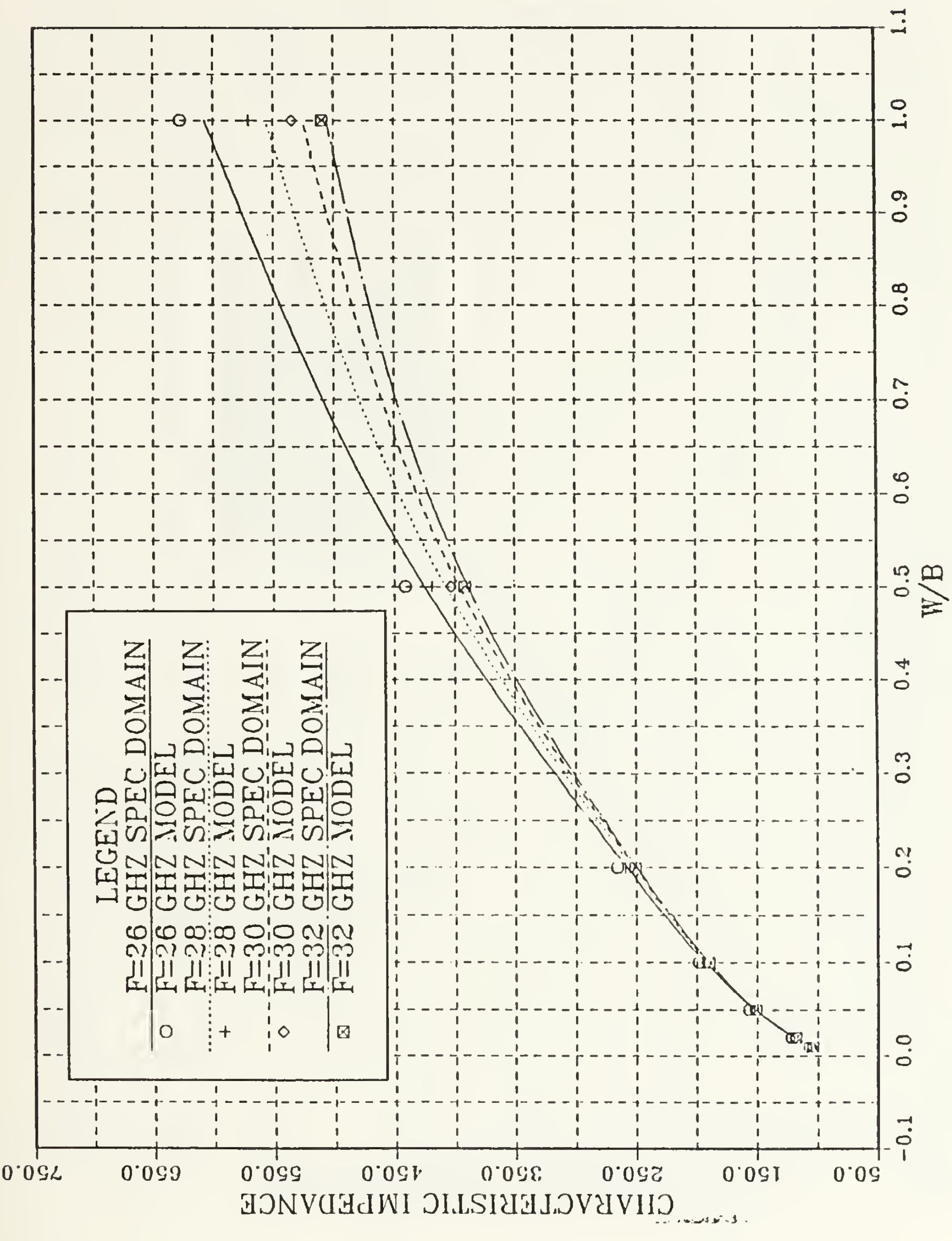

Figure 29. Impedance prediction results for Version I, $\frac{D}{a}$ =0.0357, 26-32 GHz.

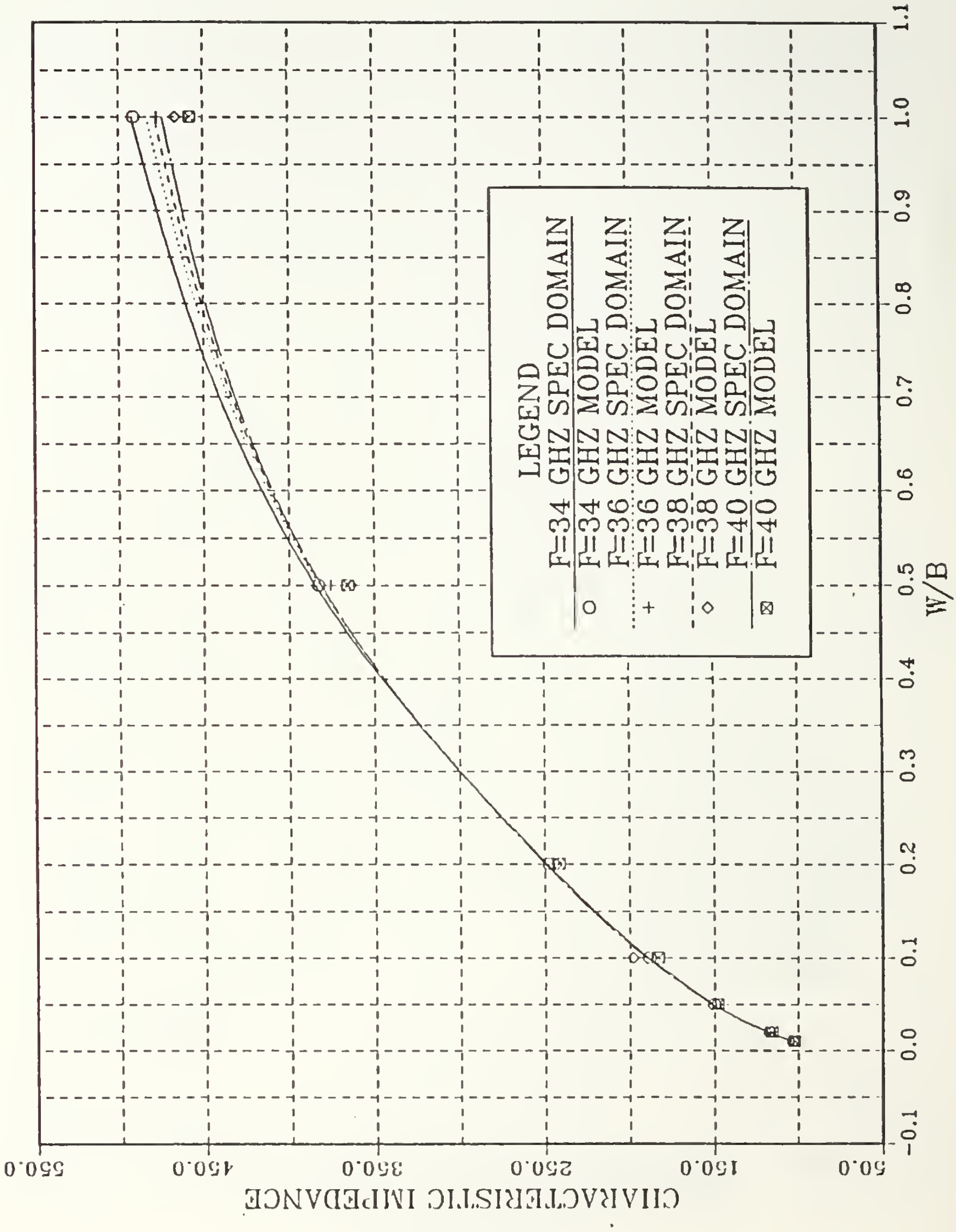

Figure 30. Impedance prediction results for Version I, $\frac{D}{a}$ =0.0357, 34-40 GHz.

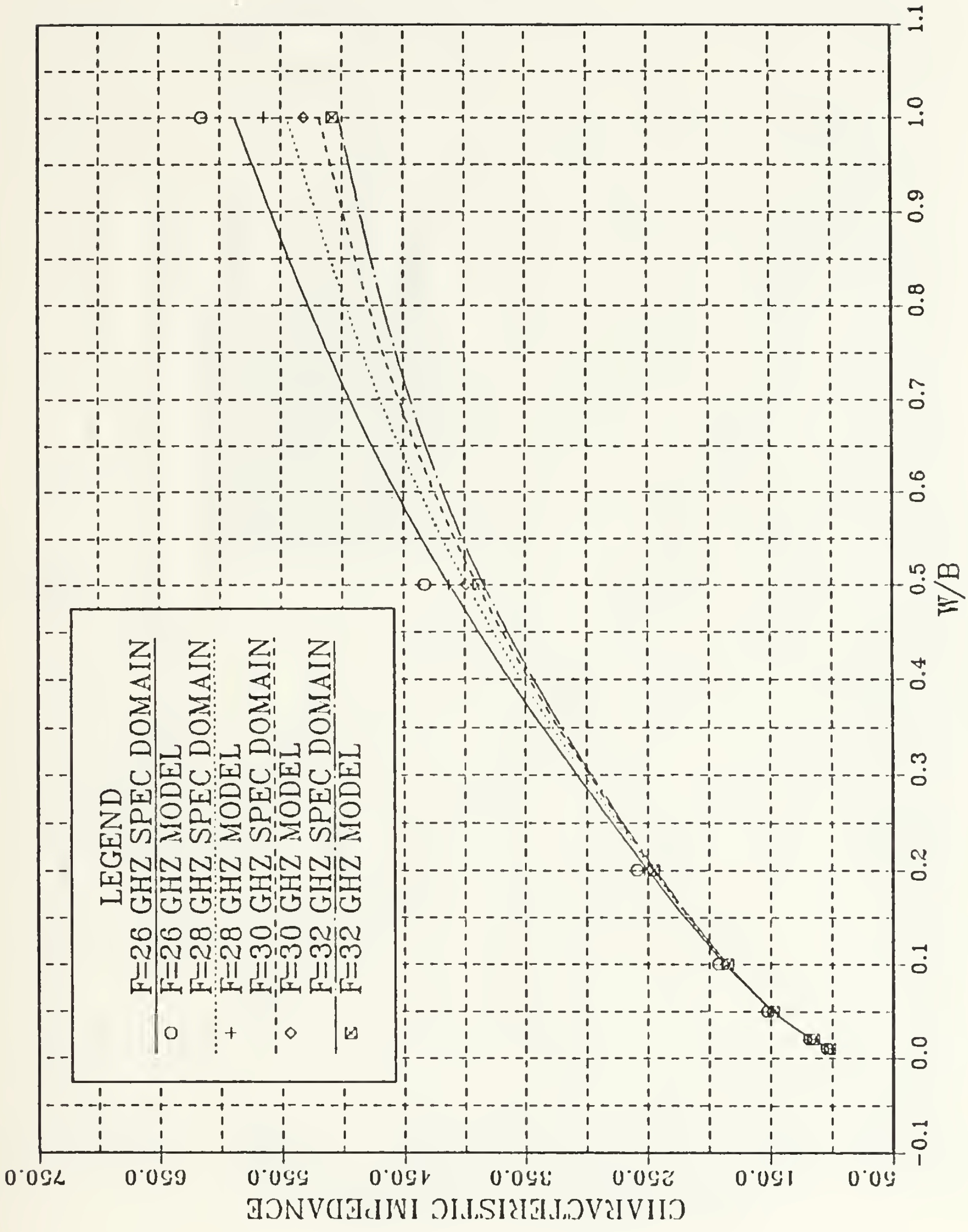

Figure 31. Impedance prediction results for Version I, $\frac{D}{a}$ =0.0536, 26-32 GHz.

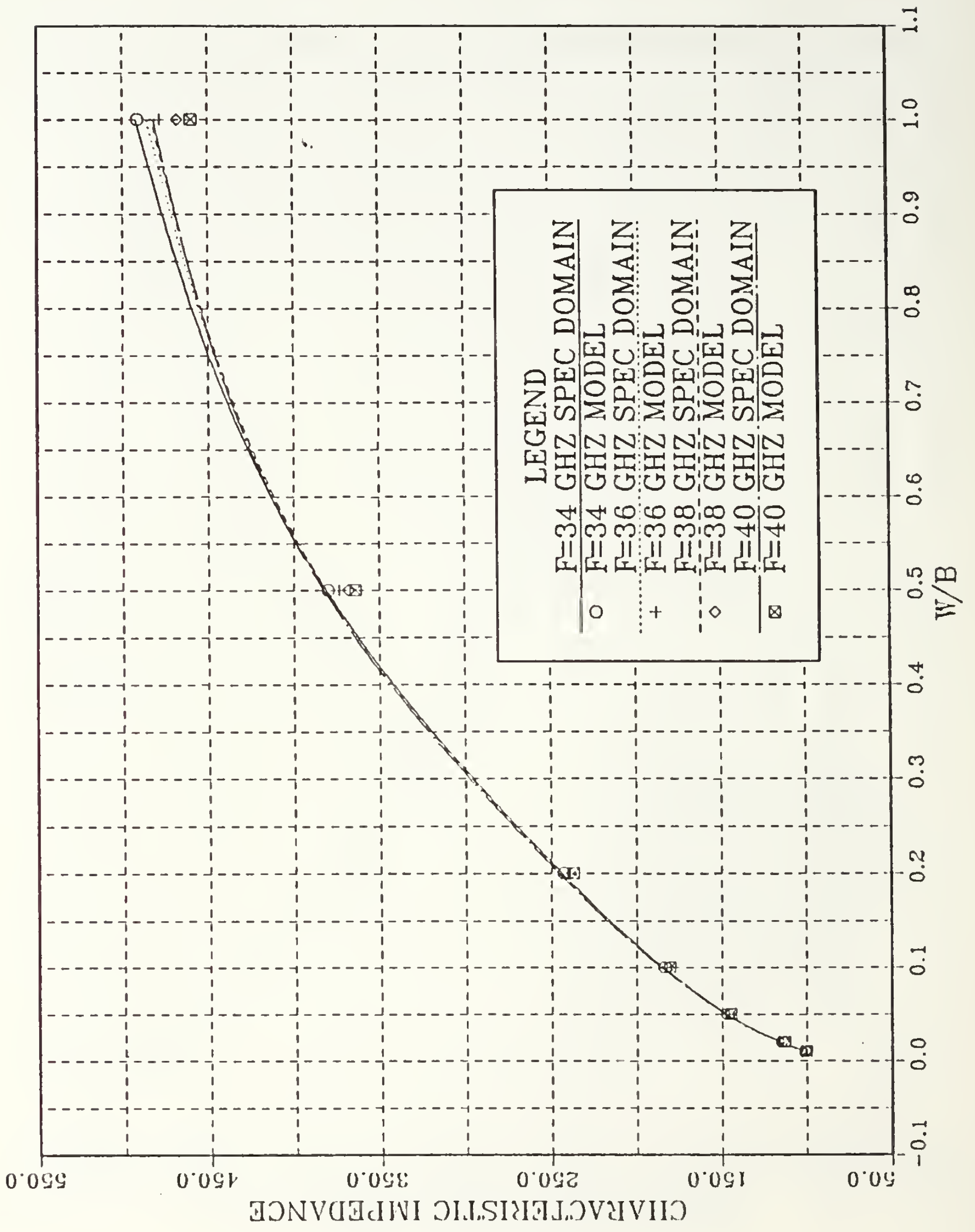

Figure 32. Impedance prediction results for Version I, $\frac{D}{a}$ =0.0536, 34-40 GHz.

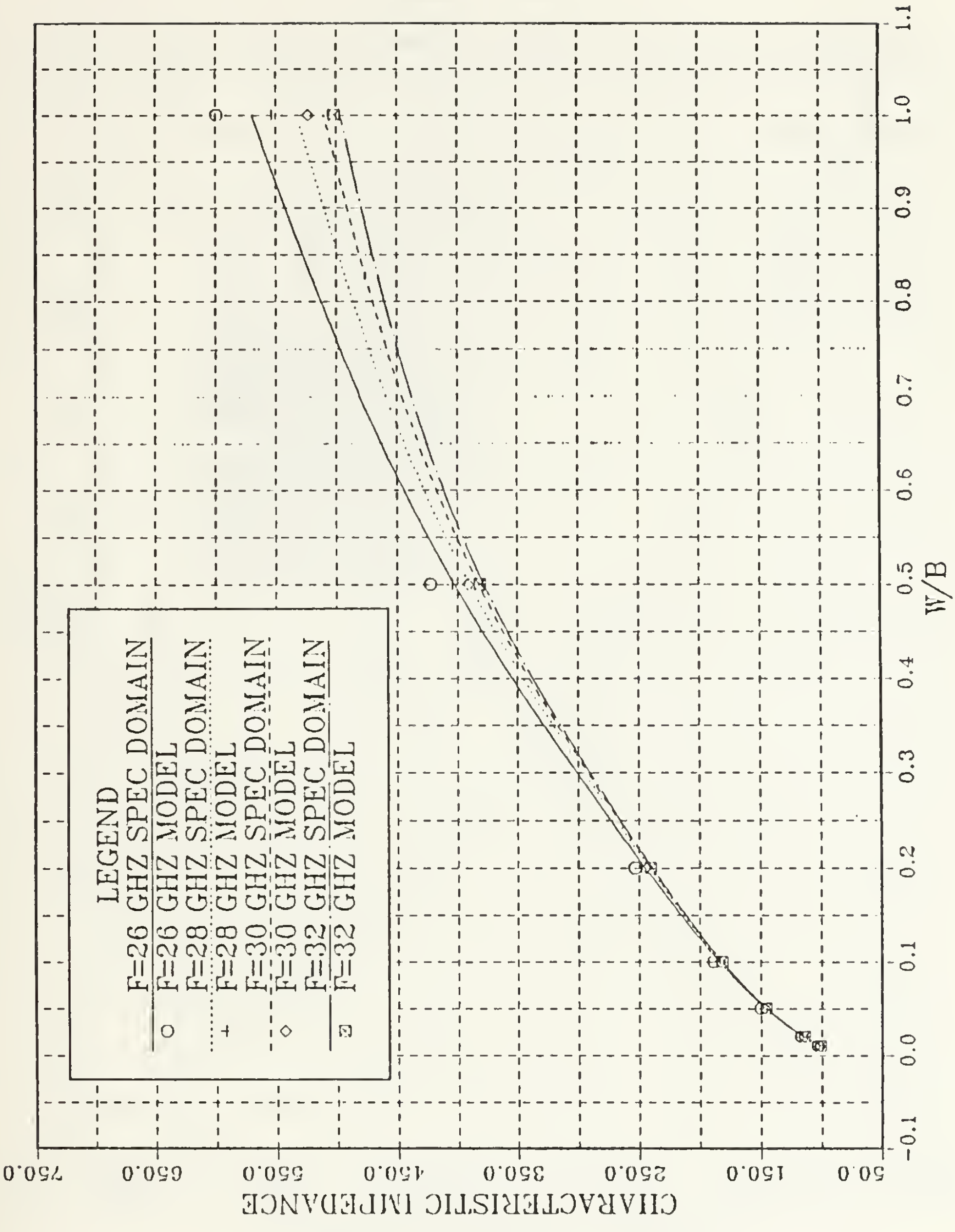

Figure 33. Impedance prediction results for Version I, $\frac{D}{a}$ =0.0714, 26-32 GHz.

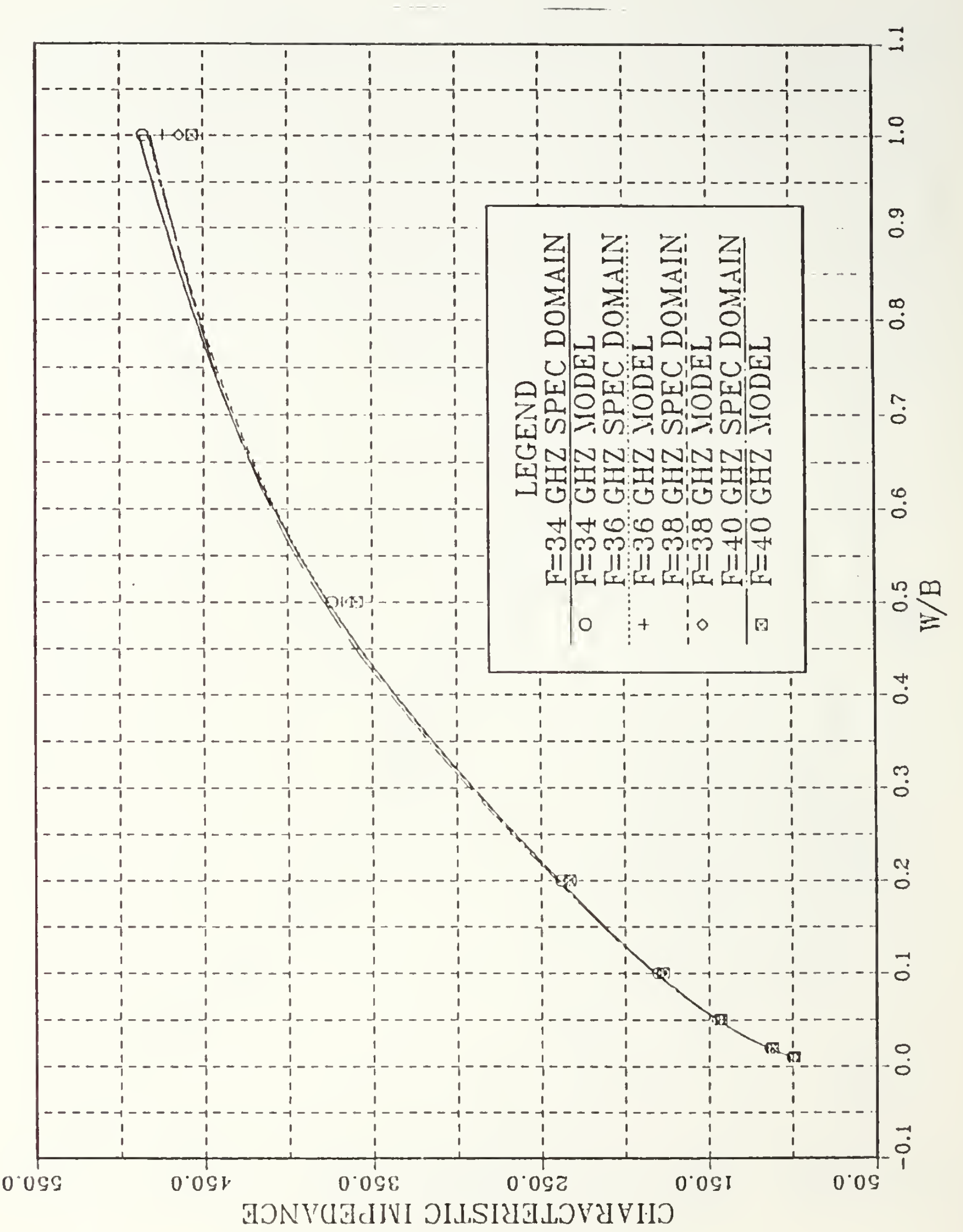

Figure 34. Impedance prediction results for Version I, $\frac{D}{a}$ =0.0714, 34-40 GHz.

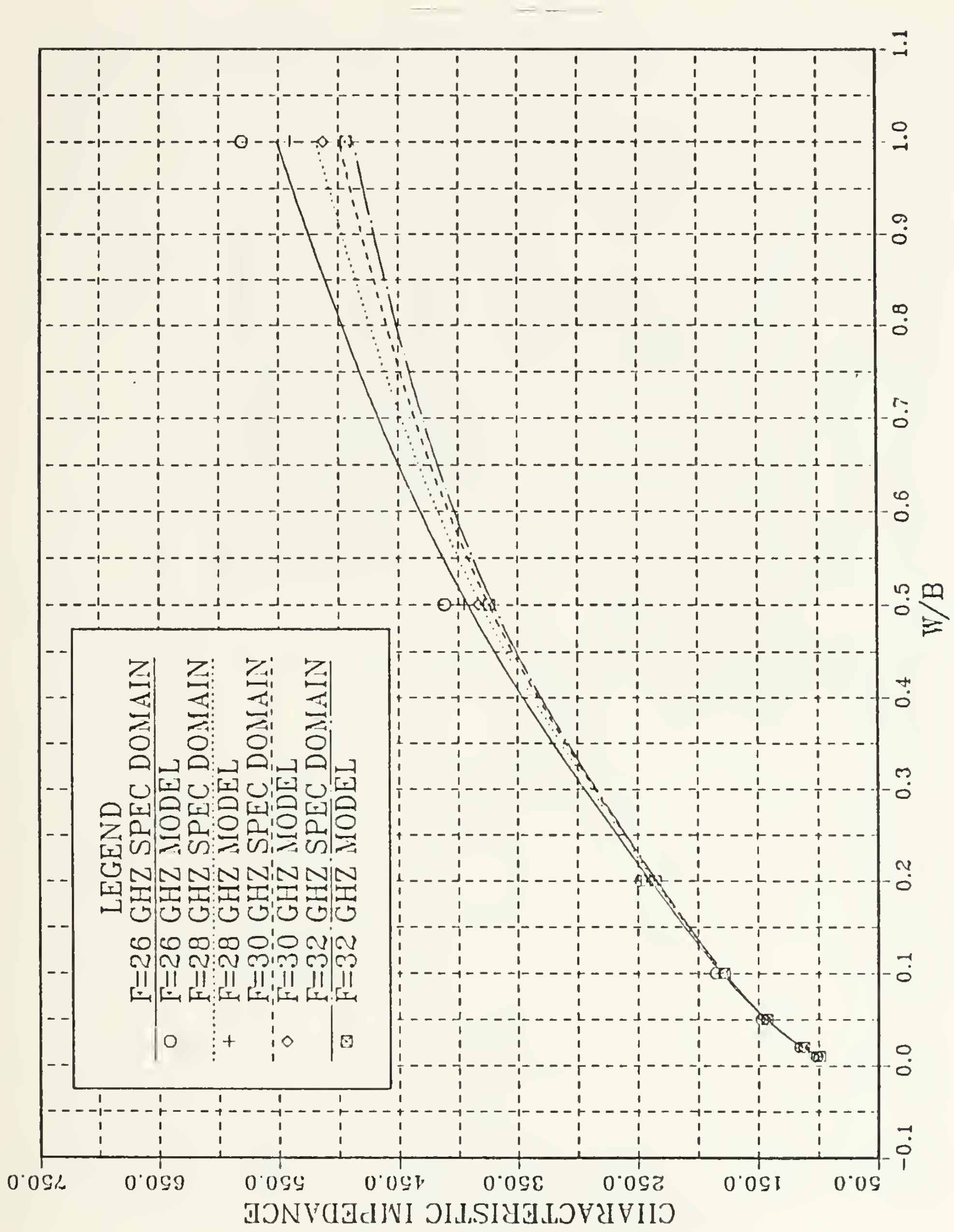

Figure 35. Impedance prediction results for Version I, $\frac{D}{a}$ =0.0893, 26-32 GHz.

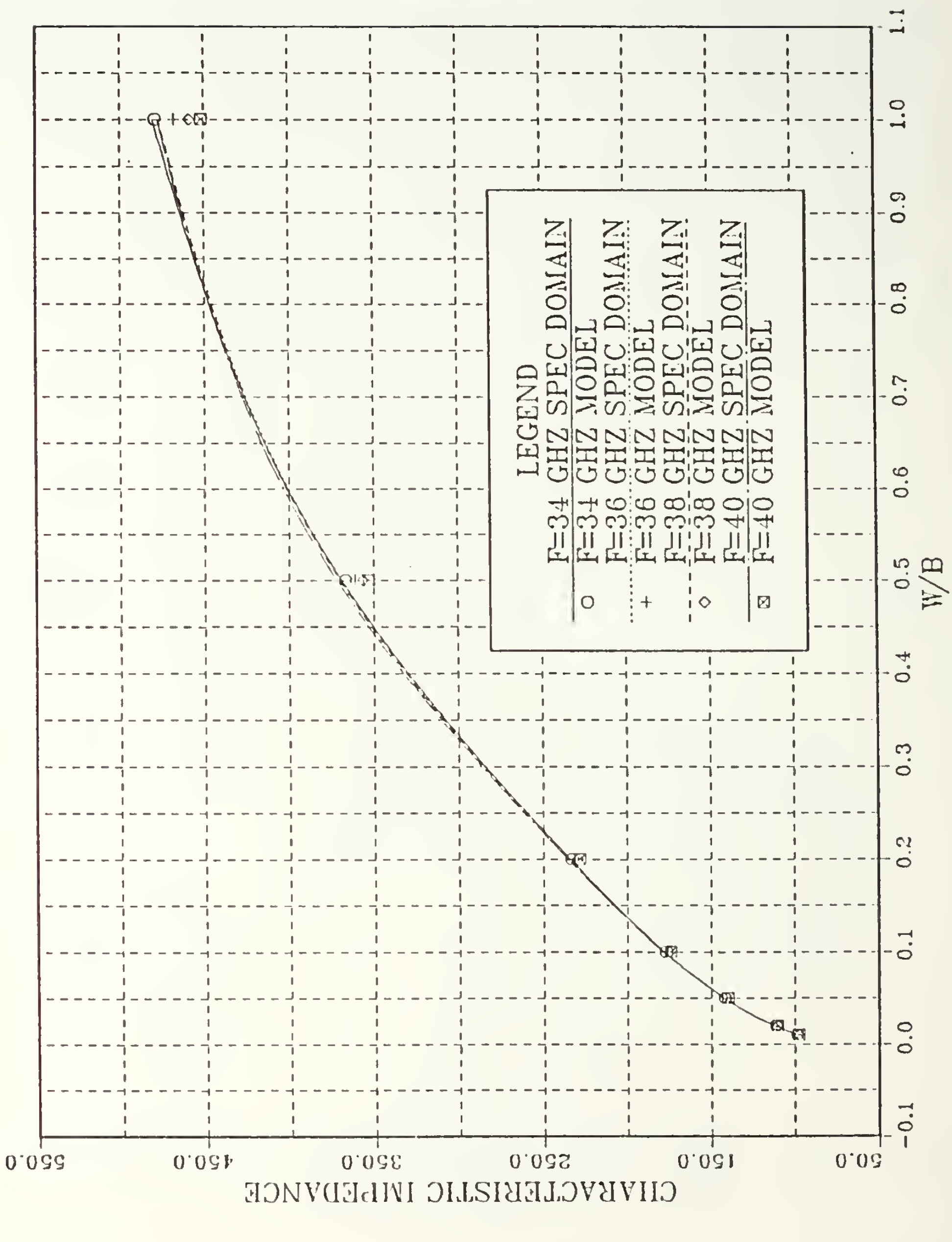

Figure 36. Impedance prediction results for Version I, $\frac{D}{a}$ =0.0893, 34-40 GHz.

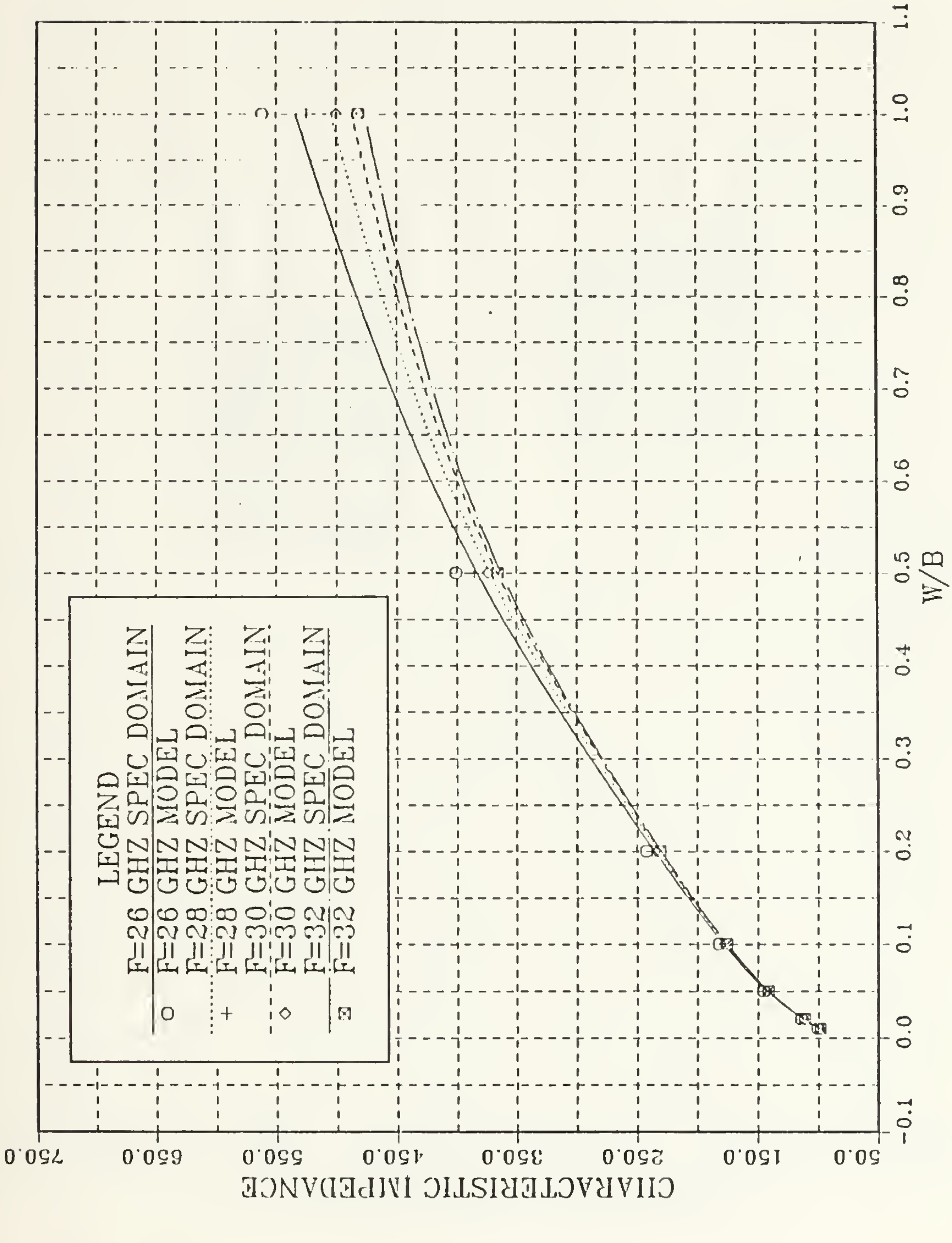

Figure 37. Impedance prediction results for Version I, $\frac{D}{a}$ =0.1071, 26-32 GHz.

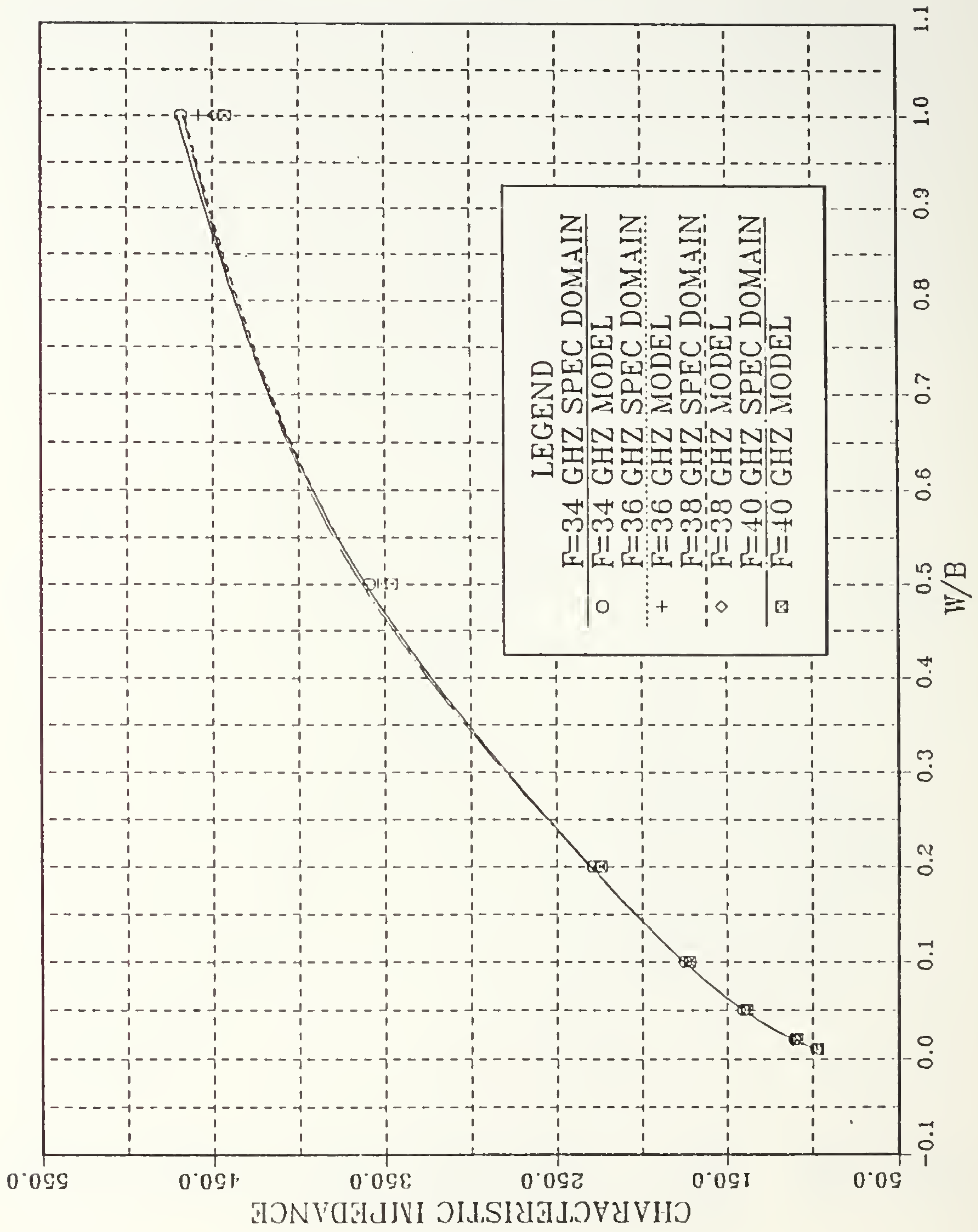

Figure 38. Impedance prediction results for Version I, $\frac{D}{a}$ =0.1071, 34-40 GHz.

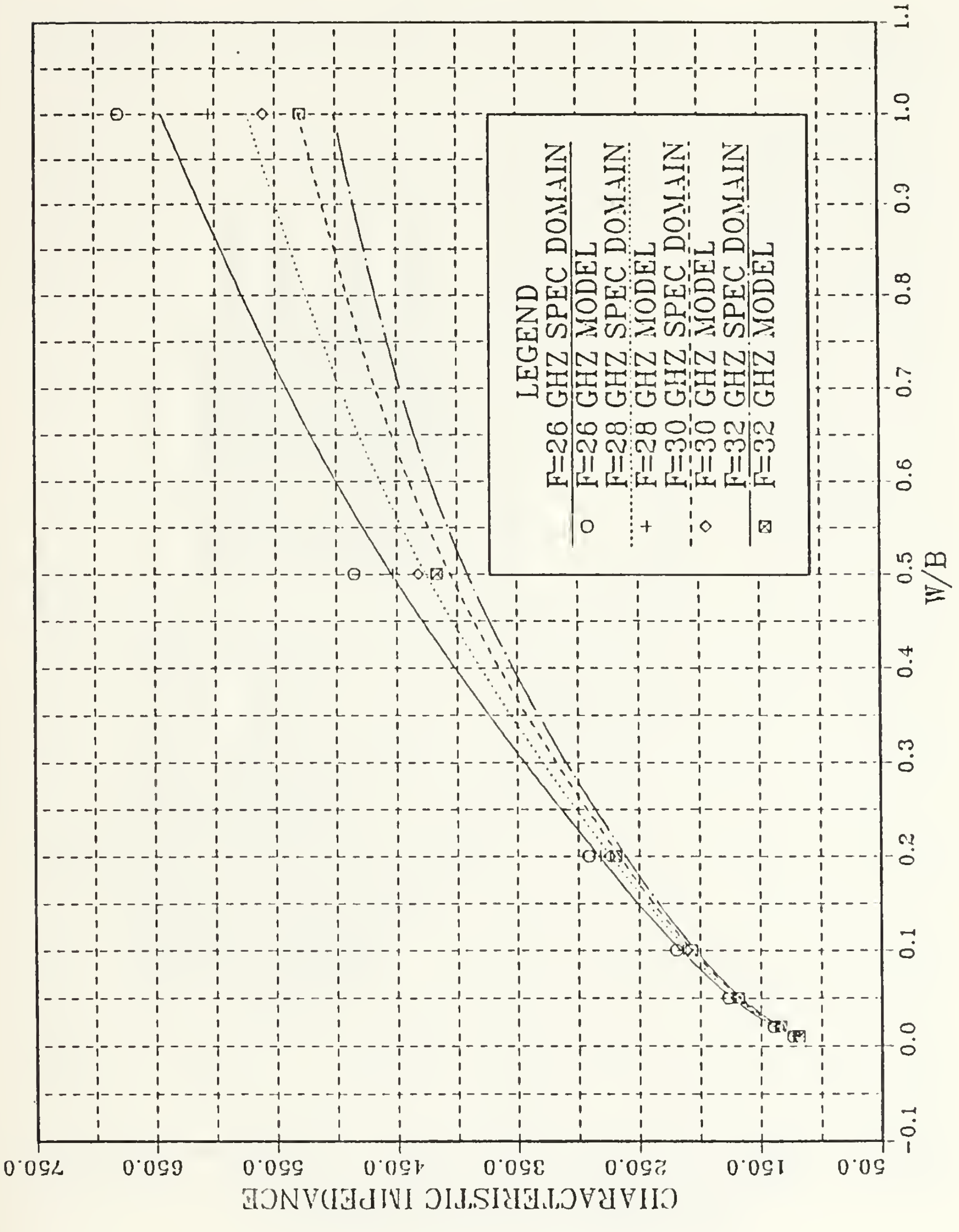

Figure 39. Impedance prediction results for Version II, $\frac{D}{a}=0$, 26-32 GHz.

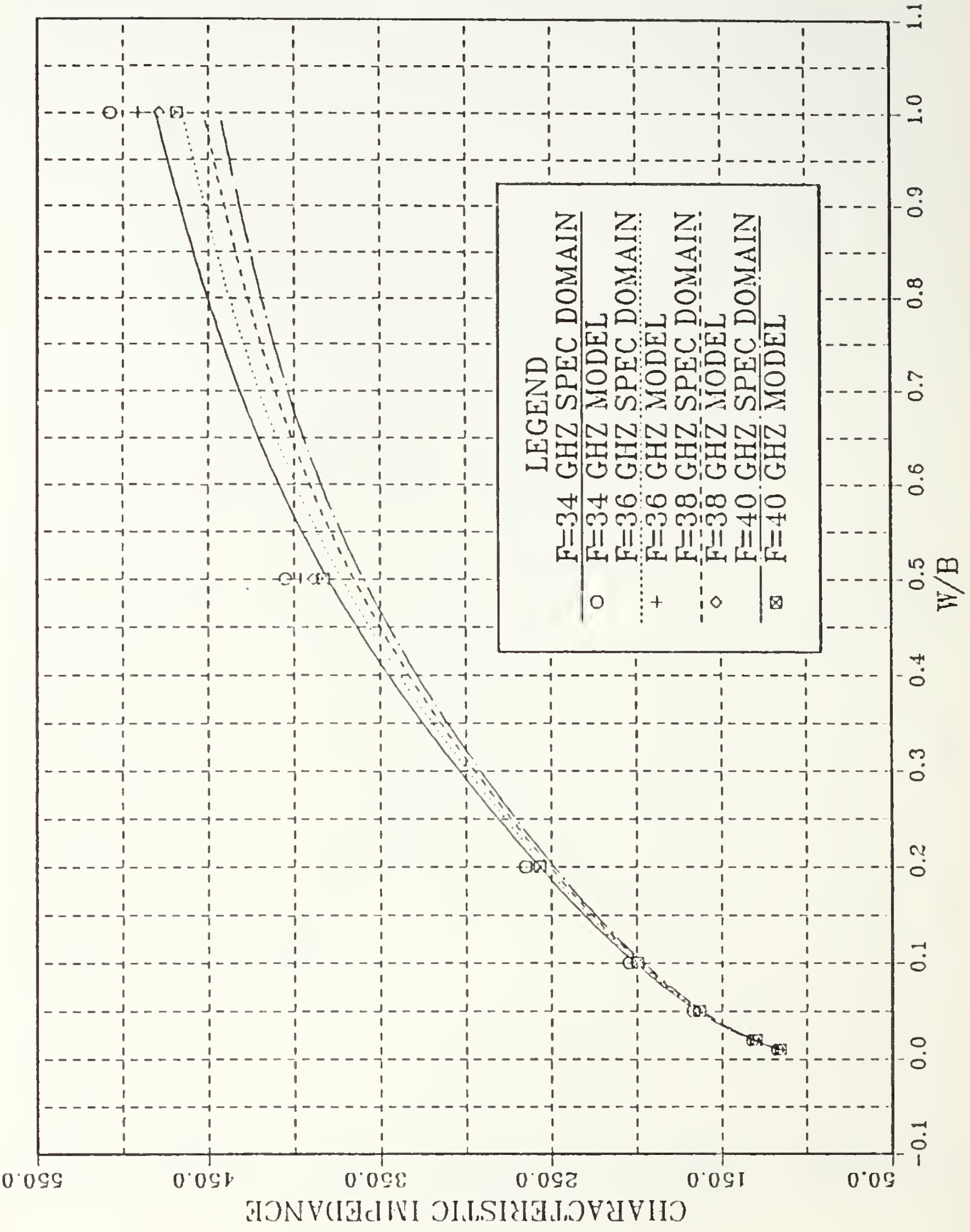

Figure 40. Impedance prediction results for Version II, $\frac{D}{a}$ =0, 34-40 GHz.

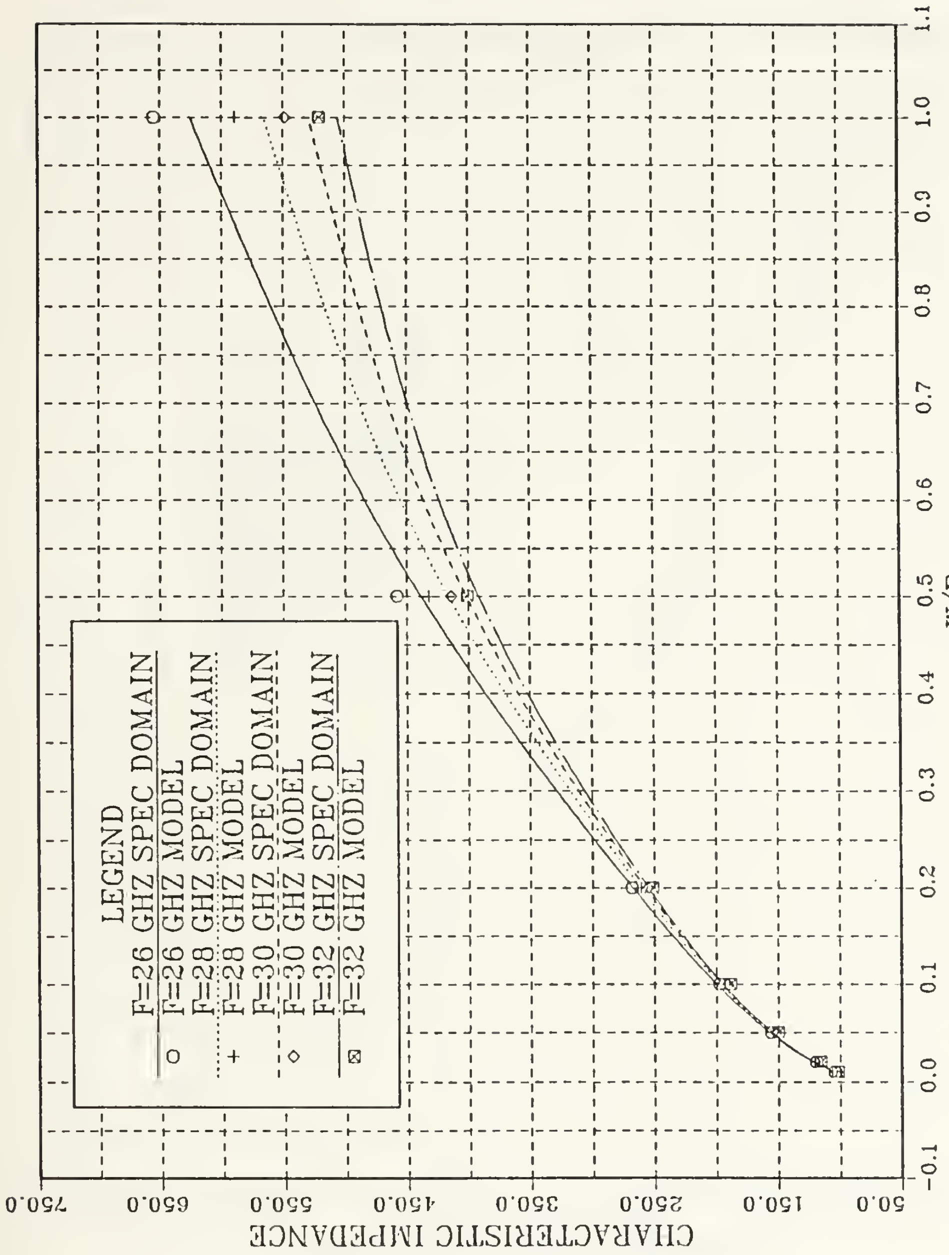

Figure 41. Impedance prediction results for Version II, $\frac{D}{a}$ =0.0179, 26-32 GHz.

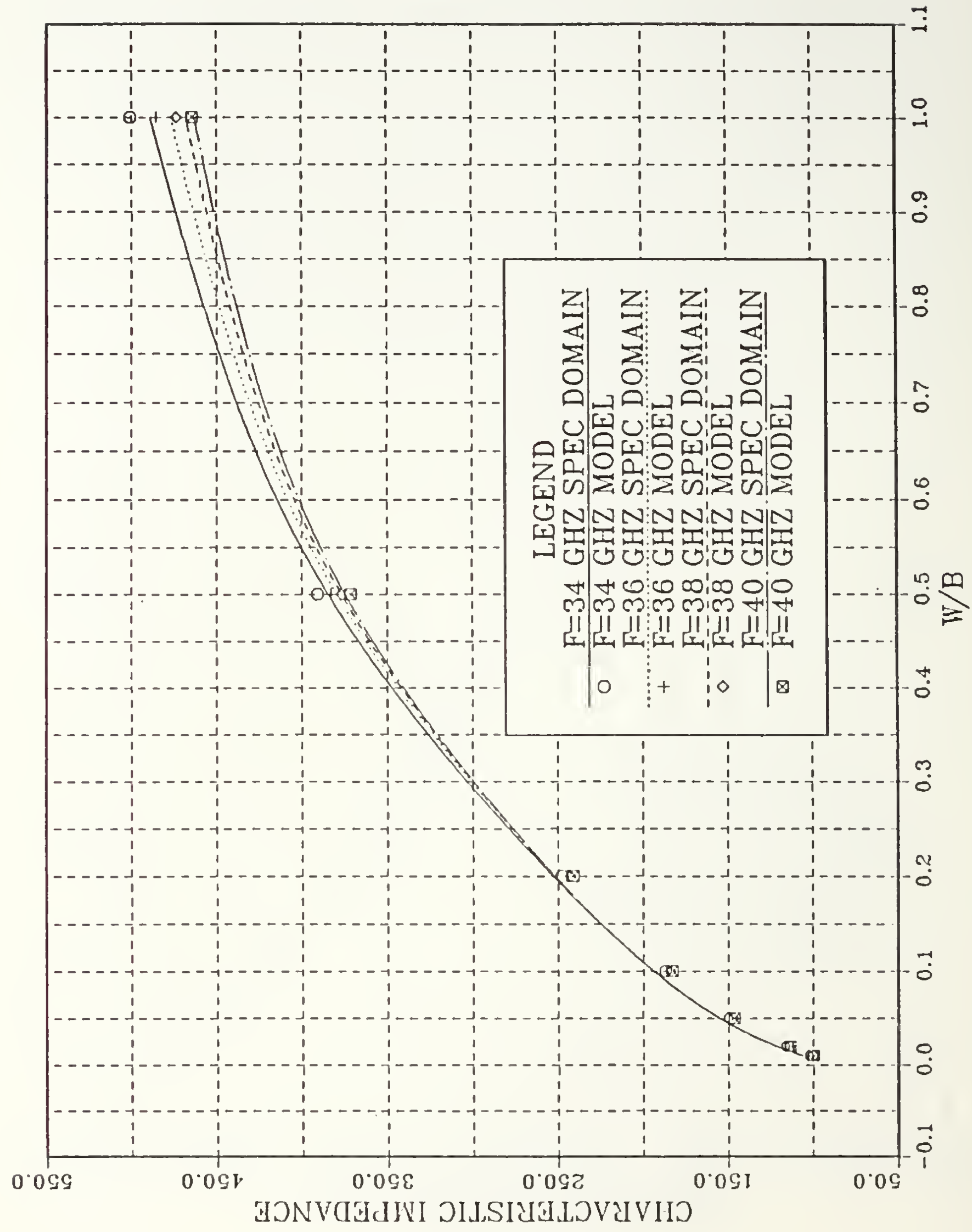

Figure 42. Impedance prediction results for Version II, $\frac{D}{a}$ =0.0179, 34-40 GHz.

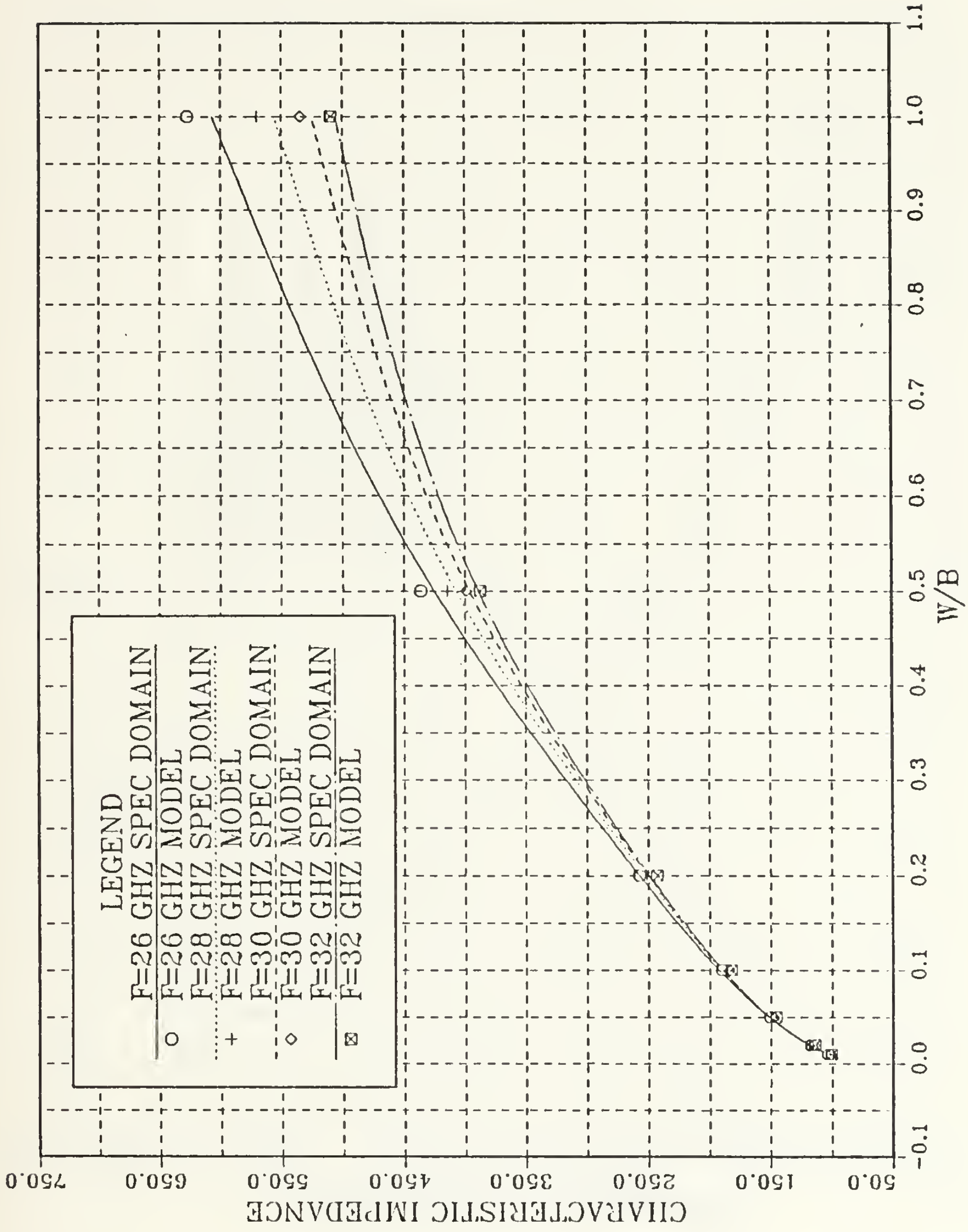

Figure 43. Impedance prediction results for Version II, $\frac{D}{a}$ =0.0357, 26-32 GHz.

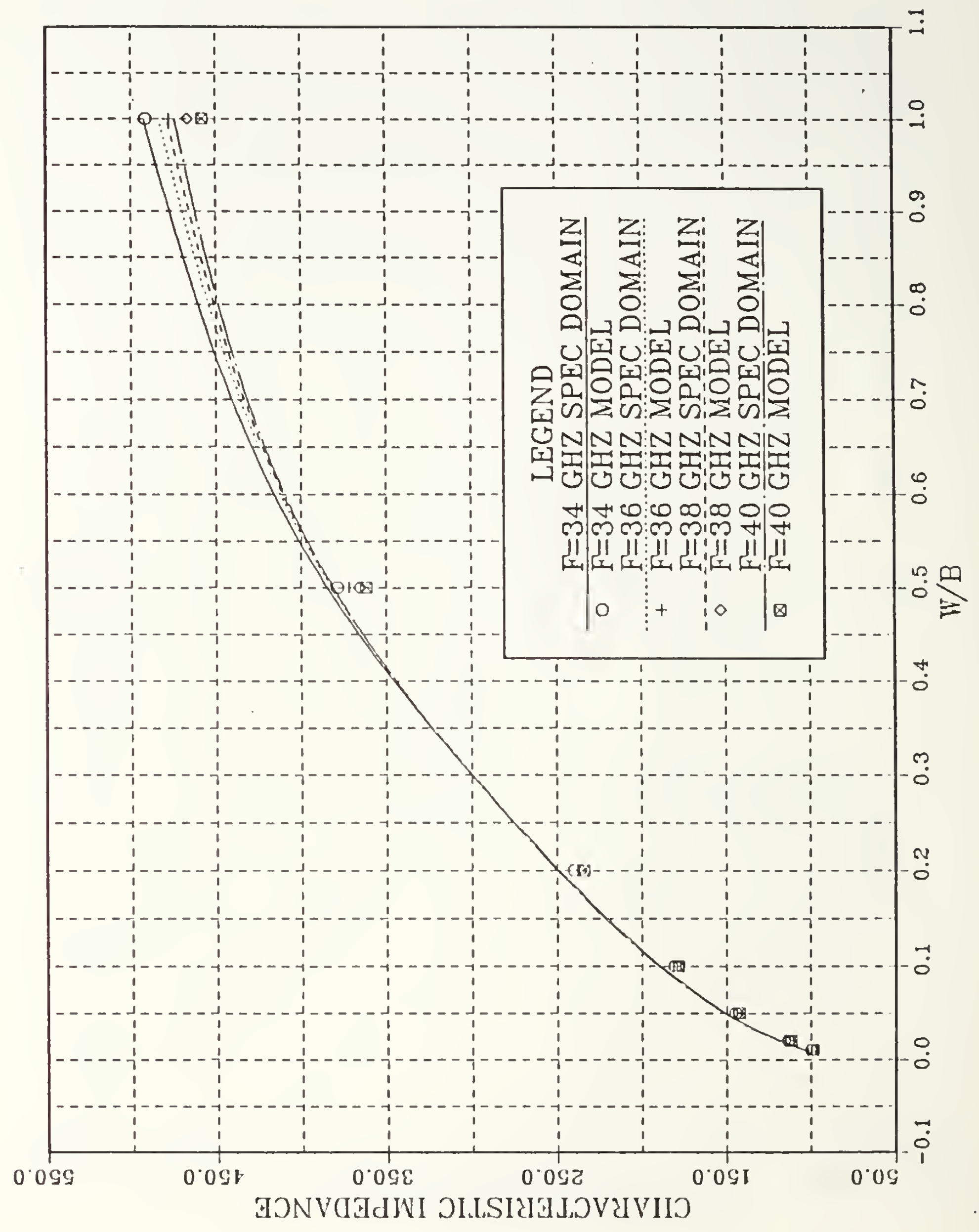

Figure 44. Impedance prediction results for Version II, $\frac{D}{a}$ =0.0357, 34-40 GHz.

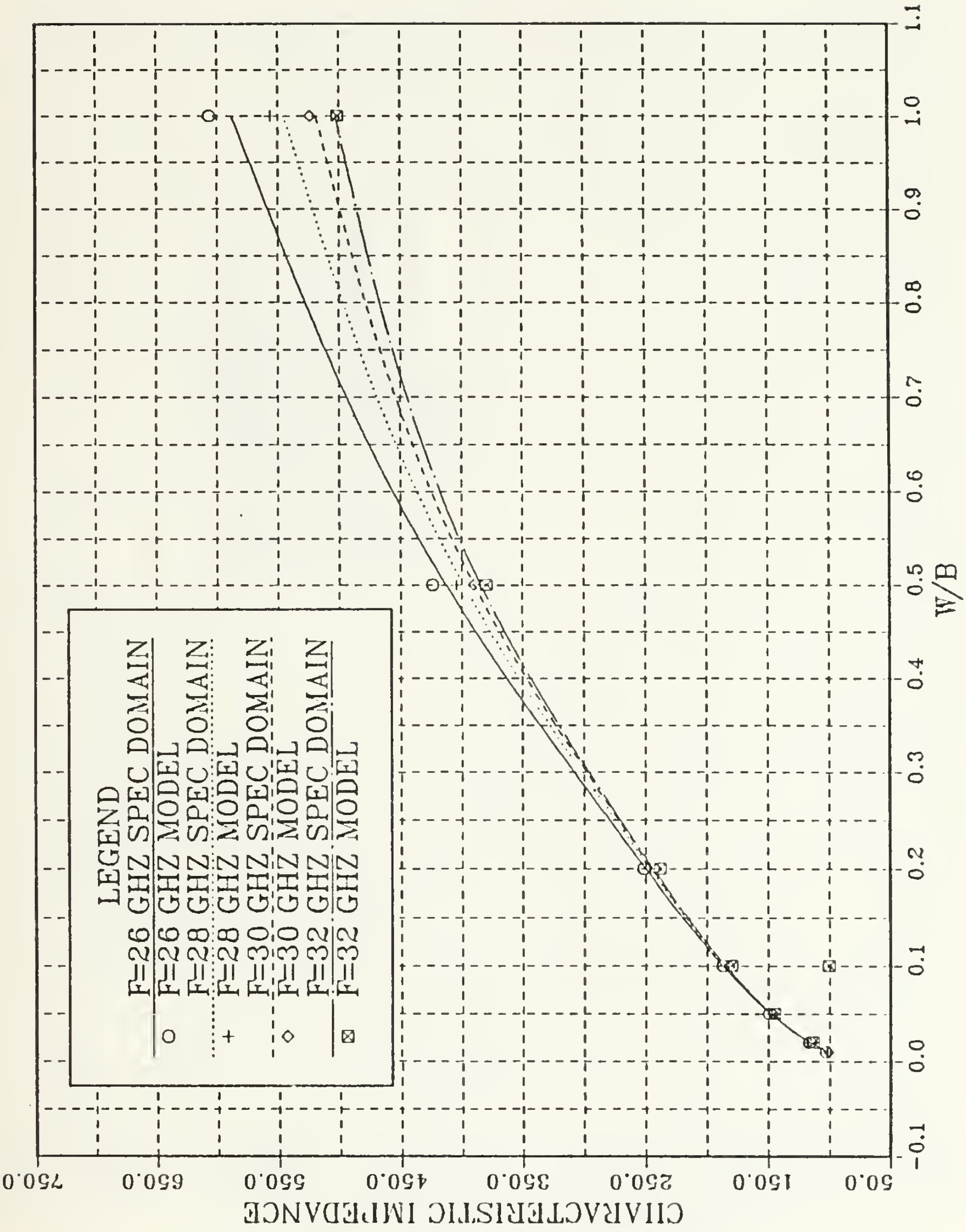

Figure 45. Impedance prediction results for Version II, $\frac{D}{a}$ =0.0536, 26-32 GHz.

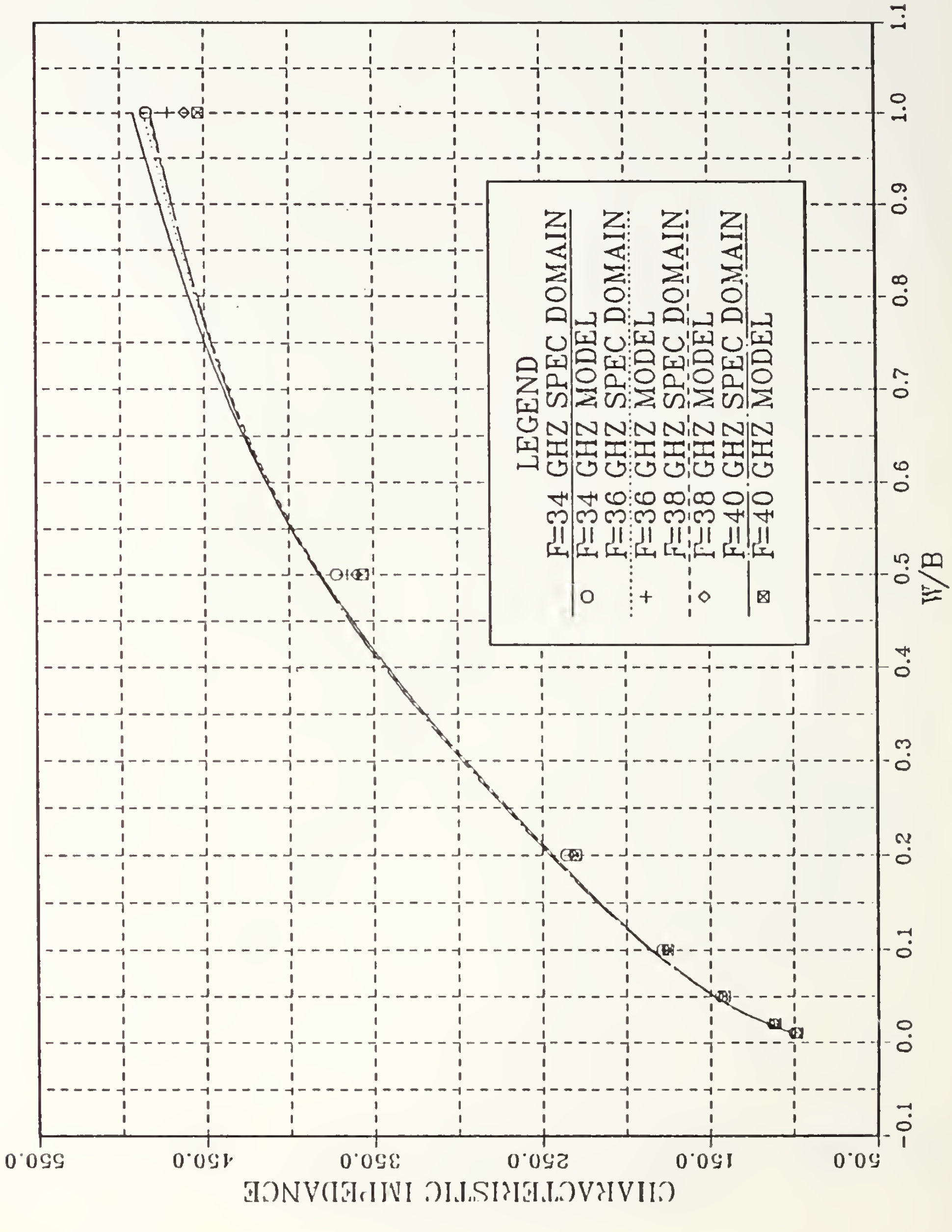

Figure 46. Impedance prediction results for Version II, $\frac{D}{a}$ =0.0536, 34-40 GHz.

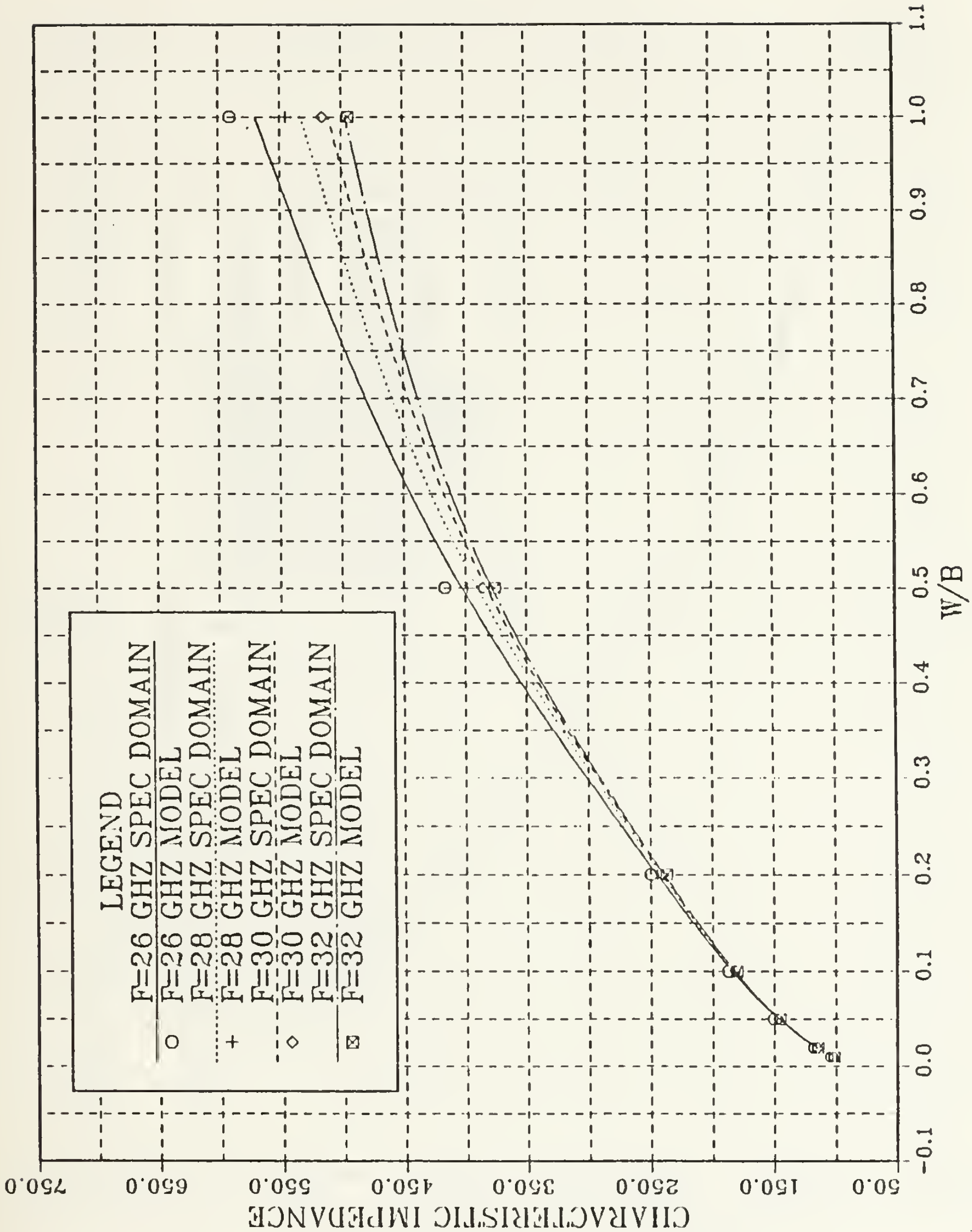

Figure 47. Impedance prediction results for Version II, $\frac{D}{a}$ =0.0714, 26-32 GHz.

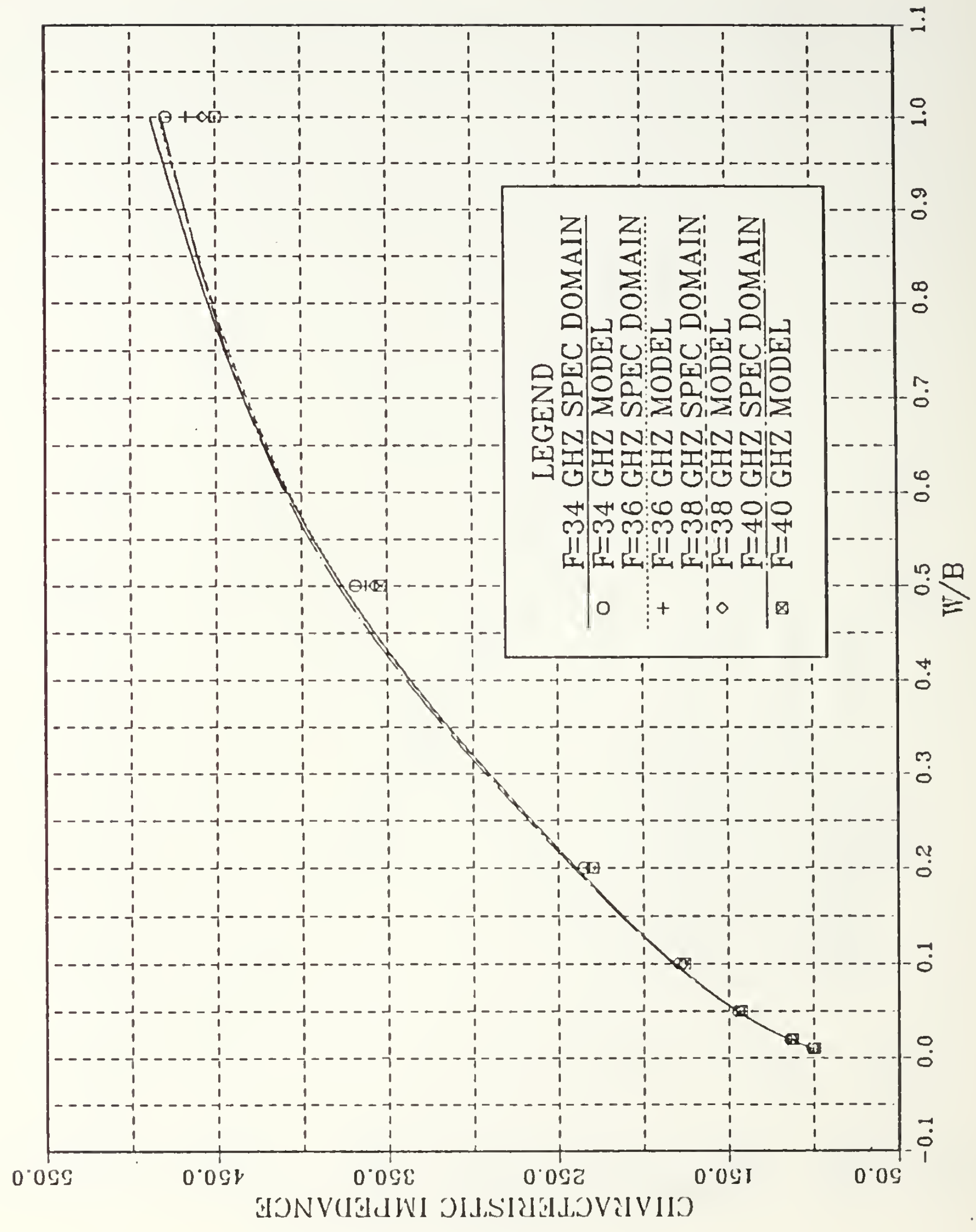

Figure 48. Impedance prediction results for Version II, $\frac{D}{a}$ =0.0714, 34-40 GHz.

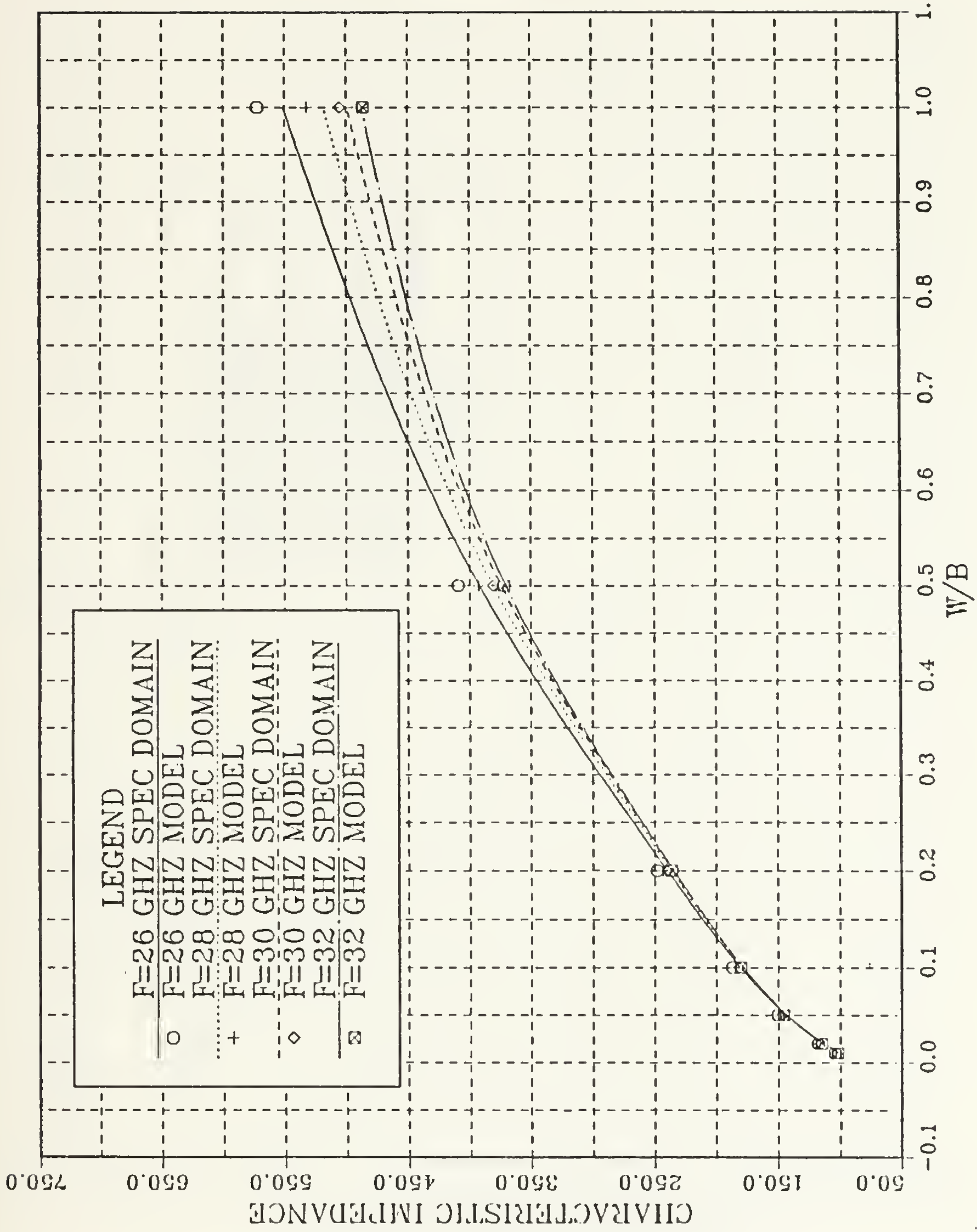

Figure 49. Impedance prediction results for Version II, $\frac{D}{a}$ =0.0893, 26-32 GHz.

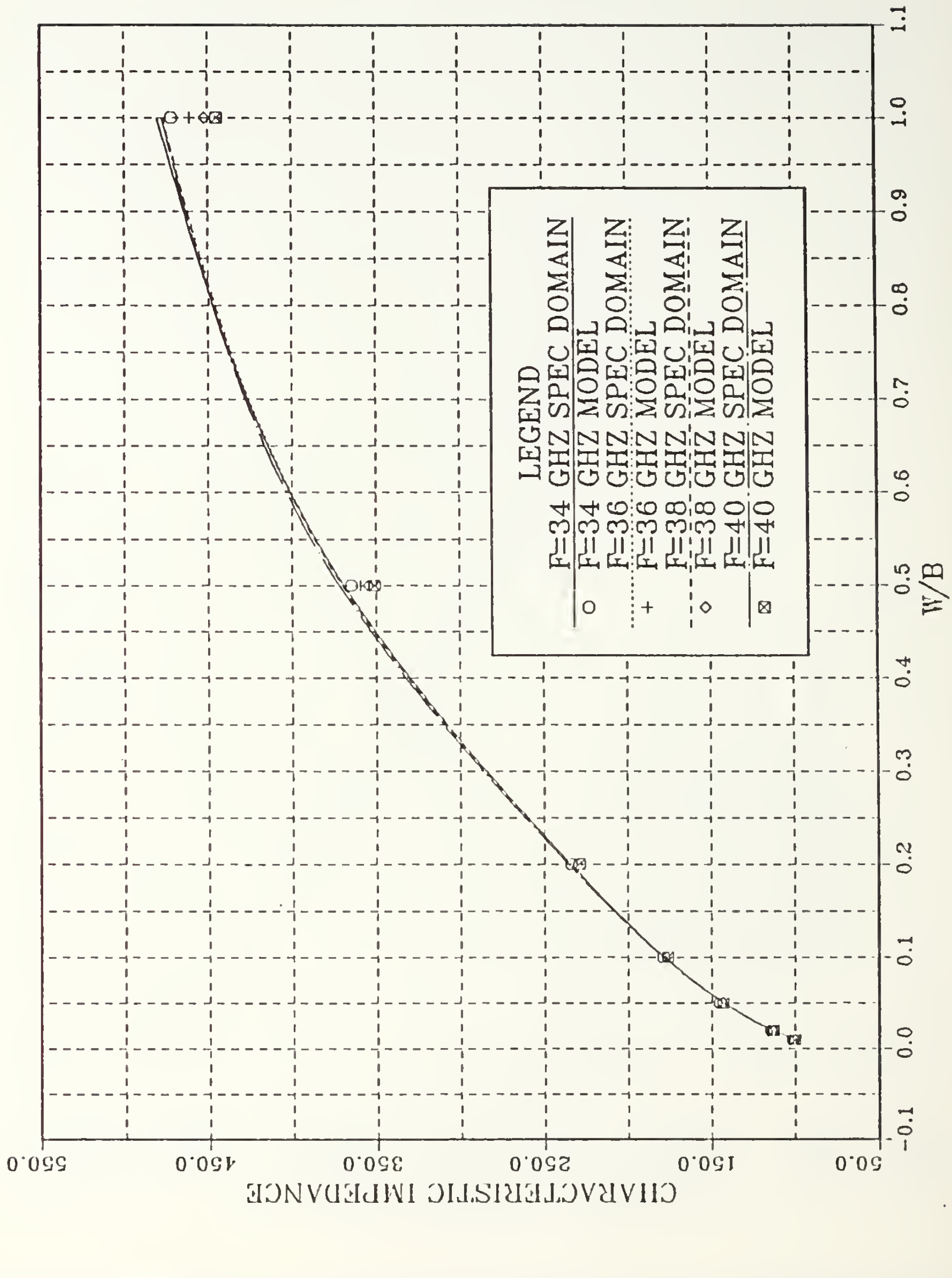

Figure 50. Impedance prediction results for Version II, $\frac{D}{a}$ =0.0893, 34-40 GHz.

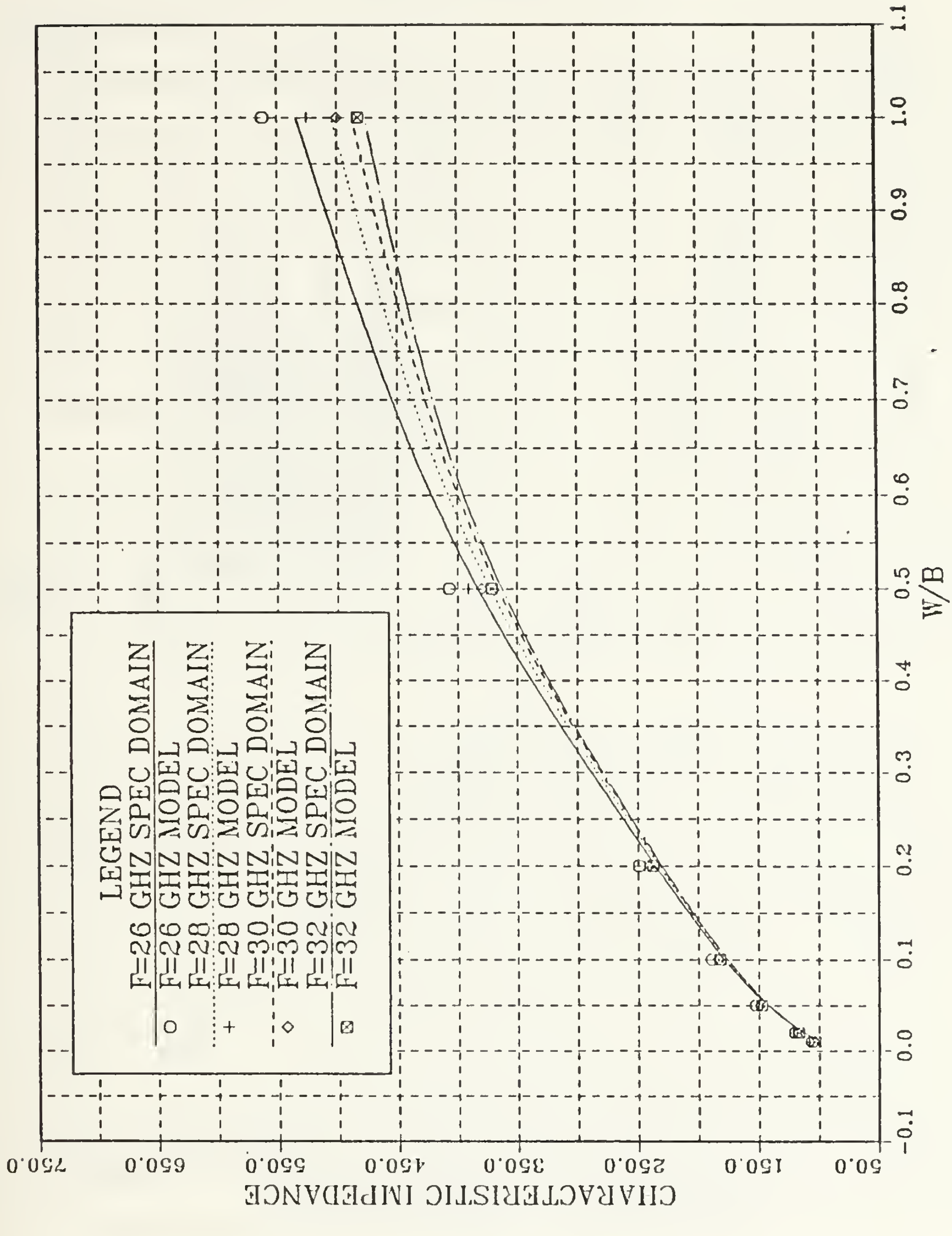

Figure 51. Impedance prediction results for Version II, $\frac{D}{a}$ =0.1071, 26-32 GHz.

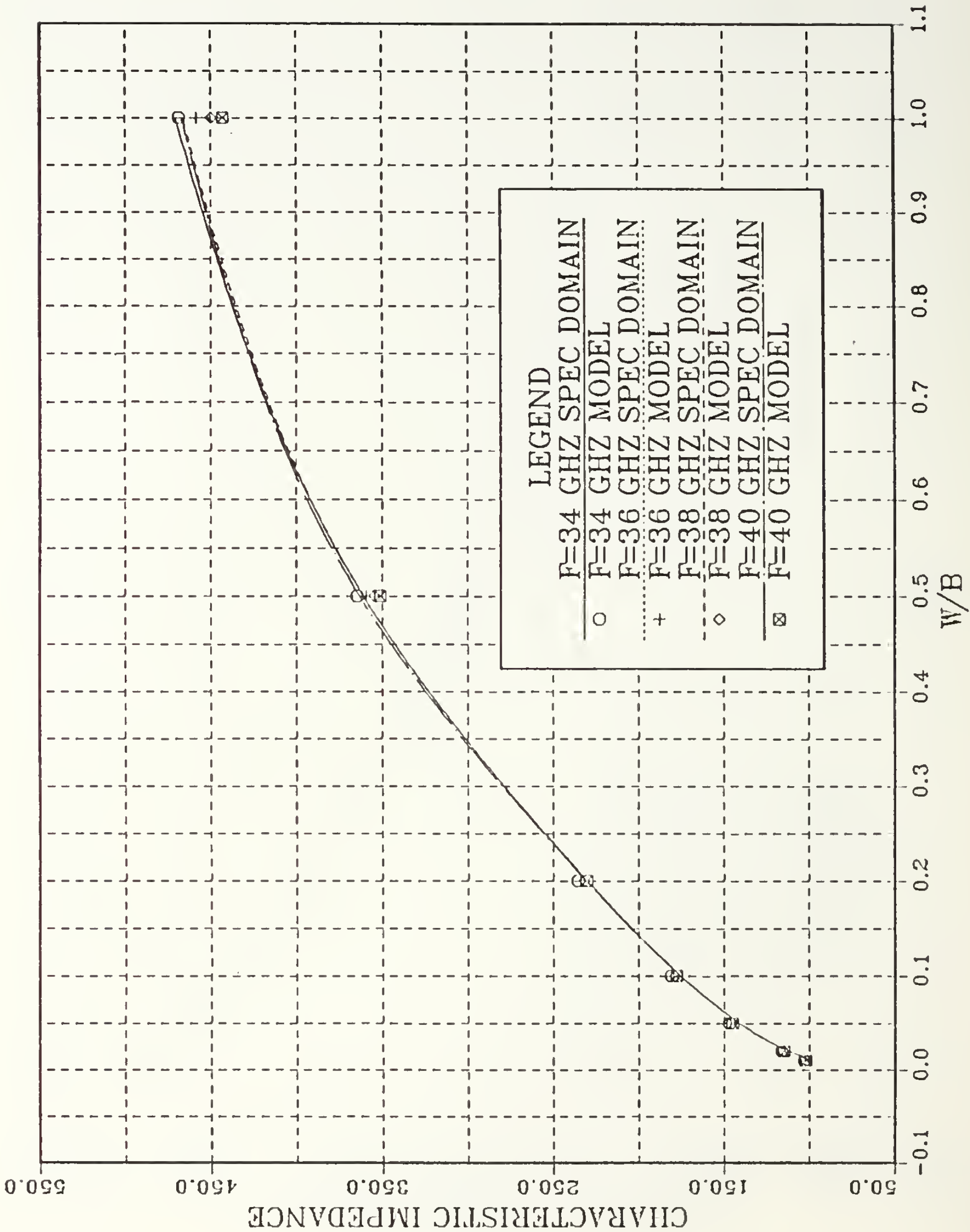

Figure 52. Impedance prediction results for Version II, $\frac{D}{a}$ =0.1071, 34-40 GHz.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This thesis develops an equivalent rectangular waveguide model for finline. Two versions have been presented, both of which may be implemented immediately in most CAD microwave circuit simulators. Both versions model the finline as a rectangular waveguide with equivalent width and height chosen to give the same wavelength and impedance at all frequencies. The maximum error for the wavelength ratio prediction in both versions is less than 1%. Version I requires seven separate expressions for the equivalent height, one for each substrate thickness under evaluation. The maximum impedance error for this version is less than 5.5%. Version II utilizes only one expression for the equivalent height, but increases the maximum impedance error by approximately 1.5%. However, Version II has an inherent advantage in that it is not restrictive in its application. Any substrate thickness may be used since the substrate thickness is normalized with respect to the finline width. This is not the case with Version I as the substrate thickness is not a variable parameter in the equivalent height equations.

Both versions are applicable to all finlines with an aspect ratio $\frac{b}{a} = \frac{1}{2}$, $\varepsilon_r = 2.22$ and $\frac{D}{a} \leq 0.1071$. Of the thirty-seven standard rectangular waveguide structures listed in the Microwave Engineers Handbook [Ref.8], thirty-three have $\frac{b}{a} = 0.5$. Due to the normalization of all variable parameters, Version II is applicable to all such finlines with any fin gap width, any substrate thickness, and throughout any microwave or millimeterwave frequency band. The same is true for Version I with the exception of the substrate thickness.

An important aspect of the model not to be overlooked is the possibility for immediate implementation using current CAD software. Although a great deal of time and effort was expended in developing this model, a CAD model requiring special software development would have greatly exceeded the cost in terms of both time and dollars.

B. RECOMMENDATIONS

Although this model has far-ranging applications, it is by no means comprehensive regarding all finline structures. As stated in the introduction, the finline used in this thesis was restricted to having centrally positioned fins and a dielectric constant of 2.22.

A possible area of interest would be to investigate the effect of moving the fins off-center, first with $\varepsilon_r = 1$ and then increasing the dielectric constant so that $\varepsilon_r = 2.22$.

The model described here was developed using only finline width, height, substrate thickness, and fin gap width as parameters. It would be interesting and useful to incorporate frequency as a parameter. This may quite possibly reduce the overall impedance error by as much as 4%.

APPENDIX A. NUMERICAL DATA FOR $\frac{D}{A}=0$

The numerical data presented in this Appendix was generated utilizing the spectral domain analysis program. **Lprime** is the wavelength in the finline, **L** is the free space wavelength, and **impedance** is the voltage-power definition of characteristic impedance.

```
FREQUENCY      Lprime/L       IMPEDANCE      W over B
---------      ---------      ---------      ---------
  26.0000         1.0928       122.2535         0.0100
  28.0000         1.0787       120.6644         0.0100
  30.0000         1.0674       119.4026         0.0100
  32.0000         1.0589       118.4358         0.0100
  34.0000         1.0504       117.5462         0.0100
  36.0000         1.0447       116.9044         0.0100
  38.0000         1.0419       116.4613         0.0100
  40.0000         1.0362       115.9217         0.0100

FREQUENCY      Lprime/L       IMPEDANCE      W over B
---------      ---------      ---------      ---------
  26.0000         1.1042       138.4196         0.0200
  28.0000         1.0872       136.3173         0.0200
  30.0000         1.0759       134.8418         0.0200
  32.0000         1.0645       133.4874         0.0200
  34.0000         1.0560       132.4524         0.0200
  36.0000         1.0504       131.6830         0.0200
  38.0000         1.0447       130.9846         0.0200
  40.0000         1.0391       130.3657         0.0200

FREQUENCY      Lprime/L       IMPEDANCE      W over B
---------      ---------      ---------      ---------
  26.0000         1.1325       173.8650         0.0500
  28.0000         1.1127       170.7288         0.0500
  30.0000         1.0957       168.1437         0.0500
  32.0000         1.0815       166.0601         0.0500
  34.0000         1.0730       164.5847         0.0500
  36.0000         1.0645       163.2634         0.0500
  38.0000         1.0560       162.1167         0.0500
  40.0000         1.0504       161.2178         0.0500
```

```
FREQUENCY     Lprime/L     IMPEDANCE     W over B
---------     ---------    ---------     ---------

  26.0000       1.1693      215.9152       0.1000
  28.0000       1.1410      210.6721       0.1000
  30.0000       1.1211      206.8375       0.1000
  32.0000       1.1042      203.6966       0.1000
  34.0000       1.0900      201.1662       0.1000
  36.0000       1.0787      199.1409       0.1000
  38.0000       1.0702      197.4958       0.1000
  40.0000       1.0617      196.1254       0.1000

FREQUENCY     Lprime/L     IMPEDANCE     W over B
---------     ---------    ---------     ---------
  26.0000       1.2344      283.1277       0.2000
  28.0000       1.1919      273.4150       0.2000
  30.0000       1.1608      266.2852       0.2000
  32.0000       1.1381      260.9029       0.2000
  34.0000       1.1183      256.5937       0.2000
  36.0000       1.1042      253.1782       0.2000
  38.0000       1.0900      250.4789       0.2000
  40.0000       1.0815      248.0957       0.2000

FREQUENCY     Lprime/L     IMPEDANCE     W over B
---------     ---------    ---------     ---------
  26.0000       1.4269      454.8900       0.5000
  28.0000       1.3363      425.6773       0.5000
  30.0000       1.2740      405.6565       0.5000
  32.0000       1.2287      391.1613       0.5000
  34.0000       1.1947      380.2222       0.5000
  36.0000       1.1664      372.0154       0.5000
  38.0000       1.1466      365.0417       0.5000
  40.0000       1.1296      359.4962       0.5000

FREQUENCY     Lprime/L     IMPEDANCE     W over B
---------     ---------    ---------     ---------
  26.0000       1.7099      644.6565       1.0000
  28.0000       1.5203      573.1607       1.0000
  30.0000       1.4070      530.1048       1.0000
  32.0000       1.3306      501.1733       1.0000
  34.0000       1.2740      480.8593       1.0000
  36.0000       1.2344      465.0373       1.0000
  38.0000       1.2032      452.7044       1.0000
  40.0000       1.1778      443.1588       1.0000
```

APPENDIX B. NUMERICAL DATA FOR $\frac{D}{A}=0.0179$

The numerical data presented in this Appendix was generated utilizing the spectral domain analysis program. **Lprime** is the wavelength in the finline, **L** is the free space wavelength, and **impedance** is the voltage-power definition of characteristic impedance.

FREQUENCY	Lprime/L	IMPEDANCE	W over B
26.0000	0.9145	106.5753	0.0100
28.0000	0.9060	106.1705	0.0100
30.0000	0.9004	106.0687	0.0100
32.0000	0.8947	106.0226	0.0100
34.0000	0.8890	106.0295	0.0100
36.0000	0.8862	106.2839	0.0100
38.0000	0.8805	106.3781	0.0100
40.0000	0.8777	106.6953	0.0100

FREQUENCY	Lprime/L	IMPEDANCE	W over B
26.0000	0.9315	121.9685	0.0200
28.0000	0.9230	121.5177	0.0200
30.0000	0.9145	121.1678	0.0200
32.0000	0.9088	121.1427	0.0200
34.0000	0.9032	121.1893	0.0200
36.0000	0.8975	121.3045	0.0200
38.0000	0.8947	121.6710	0.0200
40.0000	0.8890	121.9000	0.0200

FREQUENCY	Lprime/L	IMPEDANCE	W over B
26.0000	0.9796	157.2323	0.0500
28.0000	0.9655	155.9448	0.0500
30.0000	0.9541	155.1571	0.0500
32.0000	0.9456	154.8059	0.0500
34.0000	0.9372	154.6210	0.0500
36.0000	0.9315	154.7811	0.0500
38.0000	0.9258	155.0589	0.0500
40.0000	0.9202	155.4514	0.0500

```
 FREQUENCY      Lprime/L      IMPEDANCE      W over B
 ---------      ---------     ---------      ---------

   26.0000        1.0334       199.4432        0.1000
   28.0000        1.0136       196.8691        0.1000
   30.0000        0.9994       195.3491        0.1000
   32.0000        0.9853       194.1335        0.1000
   34.0000        0.9768       193.7062        0.1000
   36.0000        0.9683       193.5435        0.1000
   38.0000        0.9598       193.6518        0.1000
   40.0000        0.9541       194.0753        0.1000

 FREQUENCY      Lprime/L      IMPEDANCE      W over B
 ---------      ---------     ---------      ---------
   26.0000        1.1155       266.9958        0.2000
   28.0000        1.0843       261.1405        0.2000
   30.0000        1.0589       257.0219        0.2000
   32.0000        1.0419       254.4799        0.2000
   34.0000        1.0277       252.8099        0.2000
   36.0000        1.0164       251.8417        0.2000
   38.0000        1.0051       251.4770        0.2000
   40.0000        0.9966       251.5719        0.2000

 FREQUENCY      Lprime/L      IMPEDANCE      W over B
 ---------      ---------     ---------      ---------
   26.0000        1.3221       438.1221        0.5000
   28.0000        1.2457       415.8023        0.5000
   30.0000        1.1947       401.2784        0.5000
   32.0000        1.1579       391.2687        0.5000
   34.0000        1.1296       384.2443        0.5000
   36.0000        1.1070       379.4027        0.5000
   38.0000        1.0872       376.5578        0.5000
   40.0000        1.0730       374.4112        0.5000

 FREQUENCY      Lprime/L      IMPEDANCE      W over B
 ---------      ---------     ---------      ---------
   26.0000        1.6080       625.0777        1.0000
   28.0000        1.4467       565.2677        1.0000
   30.0000        1.3476       529.1392        1.0000
   32.0000        1.2797       505.3091        1.0000
   34.0000        1.2315       488.5649        1.0000
   36.0000        1.1947       476.5931        1.0000
   38.0000        1.1636       469.0719        1.0000
   40.0000        1.1410       462.8175        1.0000
```

APPENDIX C. NUMERICAL DATA FOR $\frac{D}{A}=0.0357$

The numerical data presented in this Appendix was generated utilizing the spectral domain analysis program. **Lprime** is the wavelength in the finline, **L** is the free space wavelength, and **impedance** is the voltage-power definition of characteristic impedance.

```
FREQUENCY     Lprime/L      IMPEDANCE     W over B
---------     ---------     ---------     ---------
  26.0000        0.8862      103.7107        0.0100
  28.0000        0.8777      103.3435        0.0100
  30.0000        0.8720      103.2738        0.0100
  32.0000        0.8664      103.2527        0.0100
  34.0000        0.8607      103.2764        0.0100
  36.0000        0.8579      103.5417        0.0100
  38.0000        0.8551      103.8273        0.0100
  40.0000        0.8522      104.1299        0.0100

FREQUENCY     Lprime/L      IMPEDANCE     W over B
---------     ---------     ---------     ---------
  26.0000        0.9004      118.5299        0.0200
  28.0000        0.8890      117.8932        0.0200
  30.0000        0.8834      117.8537        0.0200
  32.0000        0.8777      117.8795        0.0200
  34.0000        0.8720      117.9666        0.0200
  36.0000        0.8664      118.1101        0.0200
  38.0000        0.8636      118.4982        0.0200
  40.0000        0.8607      118.9116        0.0200

FREQUENCY     Lprime/L      IMPEDANCE     W over B
---------     ---------     ---------     ---------
  26.0000        0.9343      151.6457        0.0500
  28.0000        0.9230      150.8661        0.0500
  30.0000        0.9117      150.2822        0.0500
  32.0000        0.9032      150.1241        0.0500
  34.0000        0.8975      150.3248        0.0500
  36.0000        0.8919      150.6274        0.0500
  38.0000        0.8862      151.0266        0.0500
  40.0000        0.8805      151.5152        0.0500
```

```
FREQUENCY      Lprime/L       IMPEDANCE      W over B
---------      ---------      ---------      ---------

  26.0000        0.9796       192.0590         0.1000
  28.0000        0.9598       189.9963         0.1000
  30.0000        0.9485       189.1891         0.1000
  32.0000        0.9372       188.6910         0.1000
  34.0000        0.9287       188.6819         0.1000
  36.0000        0.9202       188.9143         0.1000
  38.0000        0.9145       189.4879         0.1000
  40.0000        0.9088       190.2223         0.1000

FREQUENCY      Lprime/L       IMPEDANCE      W over B
---------      ---------      ---------      ---------
  26.0000        1.0504       257.0892         0.2000
  28.0000        1.0249       253.0087         0.2000
  30.0000        1.0023       250.2087         0.2000
  32.0000        0.9881       248.8790         0.2000
  34.0000        0.9740       248.2048         0.2000
  36.0000        0.9626       248.2275         0.2000
  38.0000        0.9541       248.7552         0.2000
  40.0000        0.9485       249.5859         0.2000

FREQUENCY      Lprime/L       IMPEDANCE      W over B
---------      ---------      ---------      ---------
  26.0000        1.2457       424.3901         0.5000
  28.0000        1.1834       407.0291         0.5000
  30.0000        1.1381       395.8301         0.5000
  32.0000        1.1042       388.7087         0.5000
  34.0000        1.0787       384.3203         0.5000
  36.0000        1.0589       381.8298         0.5000
  38.0000        1.0419       381.0173         0.5000
  40.0000        1.0277       381.4554         0.5000

FREQUENCY      Lprime/L       IMPEDANCE      W over B
---------      ---------      ---------      ---------
  26.0000        1.5231       606.3999         1.0000
  28.0000        1.3844       555.8223         1.0000
  30.0000        1.2967       525.1669         1.0000
  32.0000        1.2344       505.5230         1.0000
  34.0000        1.1891       492.6462         1.0000
  36.0000        1.1551       484.0851         1.0000
  38.0000        1.1296       478.0336         1.0000
  40.0000        1.1070       475.5643         1.0000
```

APPENDIX D. NUMERICAL DATA FOR $\frac{D}{A}=0.0536$

The numerical data presented in this Appendix was generated utilizing the spectral domain analysis program. **Lprime** is the wavelength in the finline, **L** is the free space wavelength, and **impedance** is the voltage-power definition of characteristic impedance.

FREQUENCY	Lprime/L	IMPEDANCE	W over B
26.0000	0.8720	102.0425	0.0100
28.0000	0.8636	101.6596	0.0100
30.0000	0.8579	101.5683	0.0100
32.0000	0.8522	101.5208	0.0100
34.0000	0.8494	101.7208	0.0100
36.0000	0.8437	101.7397	0.0100
38.0000	0.8409	101.9813	0.0100
40.0000	0.8381	102.2344	0.0100

FREQUENCY	Lprime/L	IMPEDANCE	W over B
26.0000	0.8834	116.3719	0.0200
28.0000	0.8749	115.9797	0.0200
30.0000	0.8664	115.6750	0.0200
32.0000	0.8607	115.6793	0.0200
34.0000	0.8551	115.7374	0.0200
36.0000	0.8522	116.0472	0.0200
38.0000	0.8466	116.1863	0.0200
40.0000	0.8437	116.5458	0.0200

FREQUENCY	Lprime/L	IMPEDANCE	W over B
26.0000	0.9117	148.3590	0.0500
28.0000	0.9004	147.6159	0.0500
30.0000	0.8890	147.0590	0.0500
32.0000	0.8834	147.1450	0.0500
34.0000	0.8749	147.1155	0.0500
36.0000	0.8692	147.4038	0.0500
38.0000	0.8664	147.9441	0.0500
40.0000	0.8607	148.3679	0.0500

```
FREQUENCY       Lprime/L        IMPEDANCE       W over B
---------       ---------       ---------       ---------

  26.0000          0.9485        187.1203          0.1000
  28.0000          0.9315        185.5200          0.1000
  30.0000          0.9202        184.8396          0.1000
  32.0000          0.9088        184.4527          0.1000
  34.0000          0.9004        184.5342          0.1000
  36.0000          0.8919        184.8322          0.1000
  38.0000          0.8862        185.4486          0.1000
  40.0000          0.8805        186.1972          0.1000

FREQUENCY       Lprime/L        IMPEDANCE       W over B
---------       ---------       ---------       ---------
  26.0000          1.0108        250.0159          0.2000
  28.0000          0.9853        246.4813          0.2000
  30.0000          0.9683        244.6414          0.2000
  32.0000          0.9513        243.5473          0.2000
  34.0000          0.9400        243.3739          0.2000
  36.0000          0.9315        243.7324          0.2000
  38.0000          0.9230        244.4834          0.2000
  40.0000          0.9145        245.6211          0.2000

FREQUENCY       Lprime/L        IMPEDANCE       W over B
---------       ---------       ---------       ---------
  26.0000          1.1891        412.5571          0.5000
  28.0000          1.1325        398.1484          0.5000
  30.0000          1.0928        389.3198          0.5000
  32.0000          1.0617        384.0863          0.5000
  34.0000          1.0391        381.2426          0.5000
  36.0000          1.0192        380.4524          0.5000
  38.0000          1.0051        380.6191          0.5000
  40.0000          0.9909        382.5182          0.5000

FREQUENCY       Lprime/L        IMPEDANCE       W over B
---------       ---------       ---------       ---------
  26.0000          1.4495        588.0168          1.0000
  28.0000          1.3278        544.7784          1.0000
  30.0000          1.2485        518.7196          1.0000
  32.0000          1.1919        502.5251          1.0000
  34.0000          1.1523        491.9306          1.0000
  36.0000          1.1211        485.5545          1.0000
  38.0000          1.0957        482.5684          1.0000
  40.0000          1.0759        481.3699          1.0000
```

APPENDIX E. NUMERICAL DATA FOR $\frac{D}{A}=0.0714$

The numerical data presented in this Appendix was generated utilizing the spectral domain analysis program. **Lprime** is the wavelength in the finline, **L** is the free space wavelength, and **impedance** is the voltage-power definition of characteristic impedance.

FREQUENCY	Lprime/L	IMPEDANCE	W over B
26.0000	0.8636	100.8595	0.0100
28.0000	0.8551	100.4431	0.0100
30.0000	0.8494	100.3132	0.0100
32.0000	0.8437	100.2235	0.0100
34.0000	0.8381	100.1699	0.0100
36.0000	0.8352	100.3445	0.0100
38.0000	0.8324	100.5297	0.0100
40.0000	0.8296	100.7227	0.0100

FREQUENCY	Lprime/L	IMPEDANCE	W over B
26.0000	0.8720	114.7365	0.0200
28.0000	0.8636	114.3128	0.0200
30.0000	0.8551	113.9724	0.0200
32.0000	0.8494	113.9333	0.0200
34.0000	0.8466	114.1535	0.0200
36.0000	0.8409	114.1952	0.0200
38.0000	0.8381	114.4630	0.0200
40.0000	0.8352	114.7427	0.0200

FREQUENCY	Lprime/L	IMPEDANCE	W over B
26.0000	0.8975	145.9438	0.0500
28.0000	0.8862	145.1732	0.0500
30.0000	0.8749	144.5820	0.0500
32.0000	0.8692	144.6172	0.0500
34.0000	0.8636	144.7371	0.0500
36.0000	0.8579	144.9353	0.0500
38.0000	0.8522	145.2046	0.0500
40.0000	0.8494	145.6837	0.0500

```
FREQUENCY      Lprime/L      IMPEDANCE     W over B
---------      ---------     ---------     ---------

  26.0000        0.9287       183.4231       0.1000
  28.0000        0.9145       182.1331       0.1000
  30.0000        0.9004       181.1923       0.1000
  32.0000        0.8919       181.0127       0.1000
  34.0000        0.8834       181.0402       0.1000
  36.0000        0.8749       181.2670       0.1000
  38.0000        0.8692       181.7877       0.1000
  40.0000        0.8664       182.4935       0.1000

FREQUENCY      Lprime/L      IMPEDANCE     W over B
---------      ---------     ---------     ---------
  26.0000        0.9824       244.1751       0.2000
  28.0000        0.9598       241.1747       0.2000
  30.0000        0.9428       239.5138       0.2000
  32.0000        0.9287       238.7141       0.2000
  34.0000        0.9173       238.5981       0.2000
  36.0000        0.9088       238.9767       0.2000
  38.0000        0.9004       239.7128       0.2000
  40.0000        0.8919       240.7941       0.2000

FREQUENCY      Lprime/L      IMPEDANCE     W over B
---------      ---------     ---------     ---------
  26.0000        1.1466       401.8264       0.5000
  28.0000        1.0957       389.4172       0.5000
  30.0000        1.0589       381.9300       0.5000
  32.0000        1.0306       377.6900       0.5000
  34.0000        1.0079       375.7986       0.5000
  36.0000        0.9909       375.3845       0.5000
  38.0000        0.9768       376.2017       0.5000
  40.0000        0.9626       378.6825       0.5000

FREQUENCY      Lprime/L      IMPEDANCE     W over B
---------      ---------     ---------     ---------
  26.0000        1.3816       568.9552       1.0000
  28.0000        1.2740       531.9878       1.0000
  30.0000        1.2032       509.8450       1.0000
  32.0000        1.1523       496.3619       1.0000
  34.0000        1.1155       488.0562       1.0000
  36.0000        1.0872       483.3358       1.0000
  38.0000        1.0645       481.3177       1.0000
  40.0000        1.0447       482.2820       1.0000
```

APPENDIX F. NUMERICAL DATA FOR $\frac{D}{A}$ =0.0893

The numerical data presented in this Appendix was generated utilizing the spectral domain analysis program. **Lprime** is the wavelength in the finline, **L** is the free space wavelength, and **impedance** is the voltage-power definition of characteristic impedance.

FREQUENCY	Lprime/L	IMPEDANCE	W over B
26.0000	0.8551	99.6779	0.0100
28.0000	0.8494	99.4599	0.0100
30.0000	0.8437	99.2832	0.0100
32.0000	0.8381	99.1447	0.0100
34.0000	0.8324	99.0404	0.0100
36.0000	0.8296	99.1569	0.0100
38.0000	0.8268	99.2814	0.0100
40.0000	0.8239	99.4108	0.0100

FREQUENCY	Lprime/L	IMPEDANCE	W over B
26.0000	0.8636	113.3646	0.0200
28.0000	0.8551	112.8989	0.0200
30.0000	0.8494	112.7447	0.0200
32.0000	0.8437	112.6408	0.0200
34.0000	0.8381	112.5827	0.0200
36.0000	0.8352	112.7578	0.0200
38.0000	0.8296	112.7645	0.0200
40.0000	0.8268	112.9711	0.0200

FREQUENCY	Lprime/L	IMPEDANCE	W over B
26.0000	0.8862	143.8245	0.0500
28.0000	0.8749	143.0082	0.0500
30.0000	0.8664	142.6080	0.0500
32.0000	0.8579	142.3352	0.0500
34.0000	0.8522	142.3808	0.0500
36.0000	0.8466	142.4976	0.0500
38.0000	0.8437	142.8343	0.0500
40.0000	0.8381	143.0526	0.0500

```
FREQUENCY      Lprime/L      IMPEDANCE      W over B
---------      ---------     ---------      ---------
  26.0000        0.9145       180.3553        0.1000
  28.0000        0.9004       179.0278        0.1000
  30.0000        0.8890       178.2759        0.1000
  32.0000        0.8777       177.7959        0.1000
  34.0000        0.8720       177.9050        0.1000
  36.0000        0.8636       178.0067        0.1000
  38.0000        0.8579       178.3786        0.1000
  40.0000        0.8522       178.8504        0.1000

FREQUENCY      Lprime/L      IMPEDANCE      W over B
---------      ---------     ---------      ---------
  26.0000        0.9655       239.6024        0.2000
  28.0000        0.9428       236.6150        0.2000
  30.0000        0.9258       234.9387        0.2000
  32.0000        0.9117       234.0984        0.2000
  34.0000        0.9004       233.9103        0.2000
  36.0000        0.8919       234.1793        0.2000
  38.0000        0.8834       234.7795        0.2000
  40.0000        0.8777       235.5610        0.2000

FREQUENCY      Lprime/L      IMPEDANCE      W over B
---------      ---------     ---------      ---------
  26.0000        1.1127       391.7371        0.5000
  28.0000        1.0645       380.5729        0.5000
  30.0000        1.0306       373.9599        0.5000
  32.0000        1.0051       370.2096        0.5000
  34.0000        0.9824       368.7958        0.5000
  36.0000        0.9655       368.7671        0.5000
  38.0000        0.9513       369.8935        0.5000
  40.0000        0.9400       371.6804        0.5000

FREQUENCY      Lprime/L      IMPEDANCE      W over B
---------      ---------     ---------      ---------
  26.0000        1.3278       550.9058        1.0000
  28.0000        1.2287       518.3127        1.0000
  30.0000        1.1636       499.0346        1.0000
  32.0000        1.1183       487.1586        1.0000
  34.0000        1.0843       480.0315        1.0000
  36.0000        1.0560       477.0516        1.0000
  38.0000        1.0334       476.7027        1.0000
  40.0000        1.0164       477.2142        1.0000
```

APPENDIX G. NUMERICAL DATA FOR $\frac{D}{A}=0.1071$

The numerical data presented in this Appendix was generated utilizing the spectral domain analysis program. **Lprime** is the wavelength in the finline, **L** is the free space wavelength, and **impedance** is the voltage-power definition of characteristic impedance.

FREQUENCY	Lprime/L	IMPEDANCE	W over B
26.0000	0.8522	98.9846	0.0100
28.0000	0.8437	98.4877	0.0100
30.0000	0.8381	98.2671	0.0100
32.0000	0.8324	98.0830	0.0100
34.0000	0.8296	98.1259	0.0100
36.0000	0.8239	97.9943	0.0100
38.0000	0.8211	98.0622	0.0100
40.0000	0.8183	98.1329	0.0100

FREQUENCY	Lprime/L	IMPEDANCE	W over B
26.0000	0.8579	112.2629	0.0200
28.0000	0.8494	111.7455	0.0200
30.0000	0.8437	111.5330	0.0200
32.0000	0.8381	111.3684	0.0200
34.0000	0.8324	111.2475	0.0200
36.0000	0.8296	111.3499	0.0200
38.0000	0.8268	111.4603	0.0200
40.0000	0.8239	111.5755	0.0200

FREQUENCY	Lprime/L	IMPEDANCE	W over B
26.0000	0.8777	142.0130	0.0500
28.0000	0.8692	141.3917	0.0500
30.0000	0.8579	140.6651	0.0500
32.0000	0.8522	140.5286	0.0500
34.0000	0.8466	140.4650	0.0500
36.0000	0.8409	140.4689	0.0500
38.0000	0.8352	140.5339	0.0500
40.0000	0.8324	140.7725	0.0500

```
FREQUENCY      Lprime/L       IMPEDANCE      W over B
---------      ---------      ---------      ---------
  26.0000         0.9032       177.6217         0.1000
  28.0000         0.8890       176.2315         0.1000
  30.0000         0.8777       175.4037         0.1000
  32.0000         0.8692       175.0276         0.1000
  34.0000         0.8607       174.8413         0.1000
  36.0000         0.8551       174.9472         0.1000
  38.0000         0.8494       175.1538         0.1000
  40.0000         0.8437       175.4529         0.1000

FREQUENCY      Lprime/L       IMPEDANCE      W over B
---------      ---------      ---------      ---------
  26.0000         0.9485       235.0497         0.2000
  28.0000         0.9287       232.3216         0.2000
  30.0000         0.9117       230.5797         0.2000
  32.0000         0.8975       229.6518         0.2000
  34.0000         0.8890       229.3786         0.2000
  36.0000         0.8777       229.4640         0.2000
  38.0000         0.8720       229.7937         0.2000
  40.0000         0.8636       230.4626         0.2000

FREQUENCY      Lprime/L       IMPEDANCE      W over B
---------      ---------      ---------      ---------
  26.0000         1.0843       381.9752         0.5000
  28.0000         1.0391       371.6764         0.5000
  30.0000         1.0079       365.5204         0.5000
  32.0000         0.9824       362.0632         0.5000
  34.0000         0.9626       360.4732         0.5000
  36.0000         0.9456       360.4235         0.5000
  38.0000         0.9343       360.6371         0.5000
  40.0000         0.9202       363.0142         0.5000

FREQUENCY      Lprime/L       IMPEDANCE      W over B
---------      ---------      ---------      ---------
  26.0000         1.2768       532.4061         1.0000
  28.0000         1.1891       503.5834         1.0000
  30.0000         1.1296       486.2632         1.0000
  32.0000         1.0872       475.6356         1.0000
  34.0000         1.0532       470.0342         1.0000
  36.0000         1.0277       467.1196         1.0000
  38.0000         1.0079       465.9598         1.0000
  40.0000         0.9909       466.8444         1.0000
```

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